Science Afternoon at NIST
Scanning Electron Microscopy (SEM)

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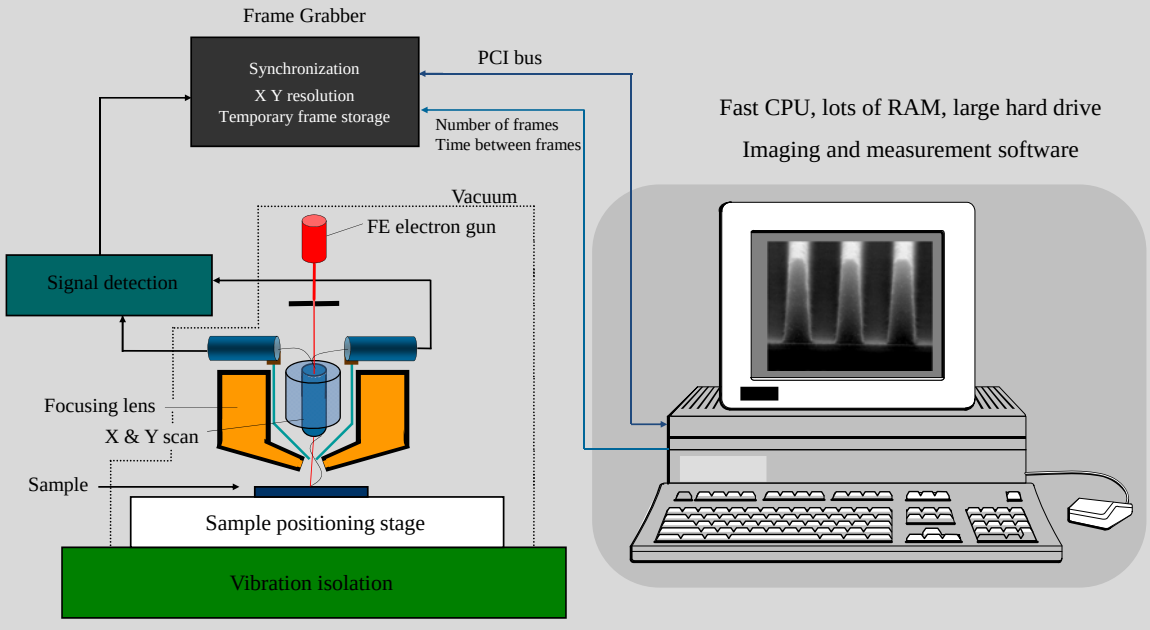
SEM and Imaging System

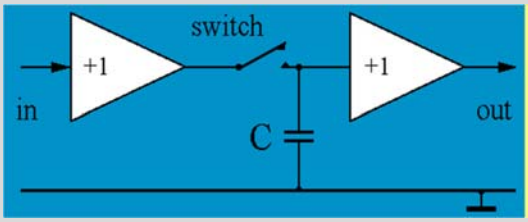


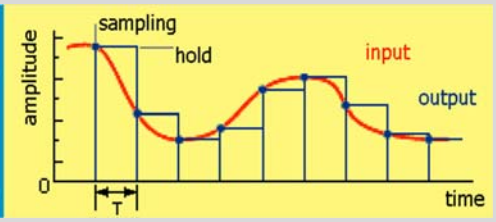
SEM

Computer

Signal Sampling

- Bandwidth (B) **:** difference between the highest (B_1) and lowest (B_0) frequency
- Nyquist (sampling) theorem**:** an analog signal may be uniquely represented by discrete samples taken at at least twice of the highest frequency (B_1)
- Sample and hold circuit keeps signal unchanged for the time of conversion
  - spot sampling (cheaper) or gated integrator (more complex, more $)

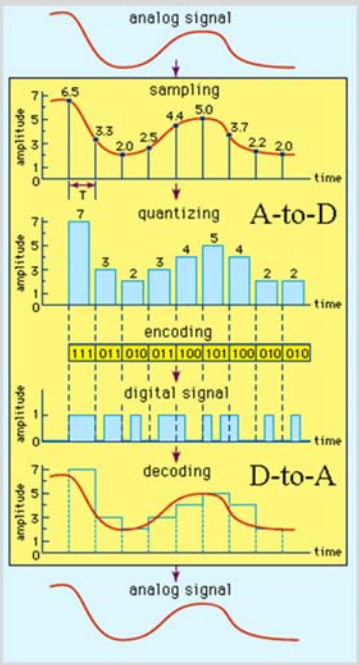




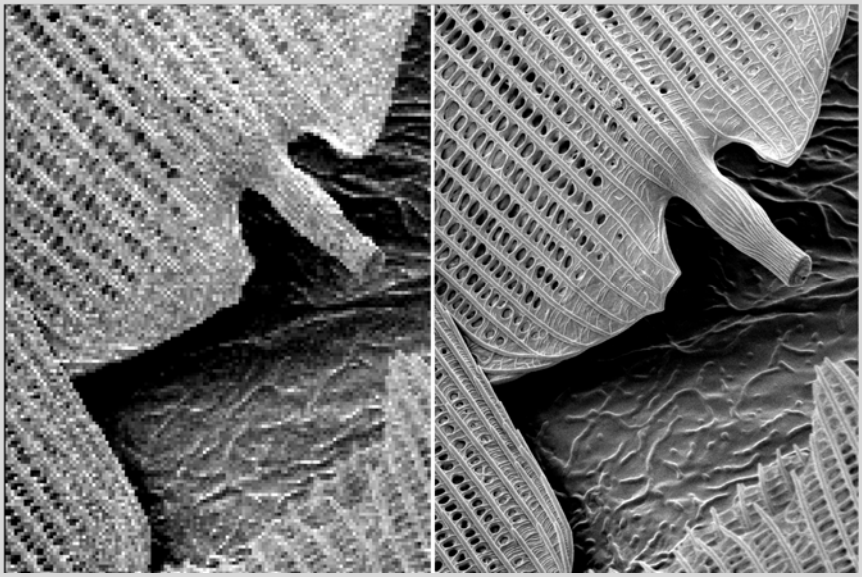
- Example: for audio CDs the 20 Hz - 20 kHz signal is sampled with 44.1 kHz

AD and DA Conversion

- Analog-to-digital conversion:
  sampling, quantizing, encoding
- Digital-to-analog conversion:
  decoding, filtering
- Noise, distortion, non-linearity: resolution dependent for both AD + DA processes
- Signal-to-noise ratio (theoretical):
  8 bit ADC 48 dB ~250 to 1
  12 bit ADC 70 dB ~3100 to 1
- Speed of conversion:
  100 ksamples/s 12 bit AD converter
  0.1 1024x1024 image/s; 25 ns/pixel
  10 Msamples/s 12 bit AD converter
  10 1024x1024 image/s; 6 ns/pixel



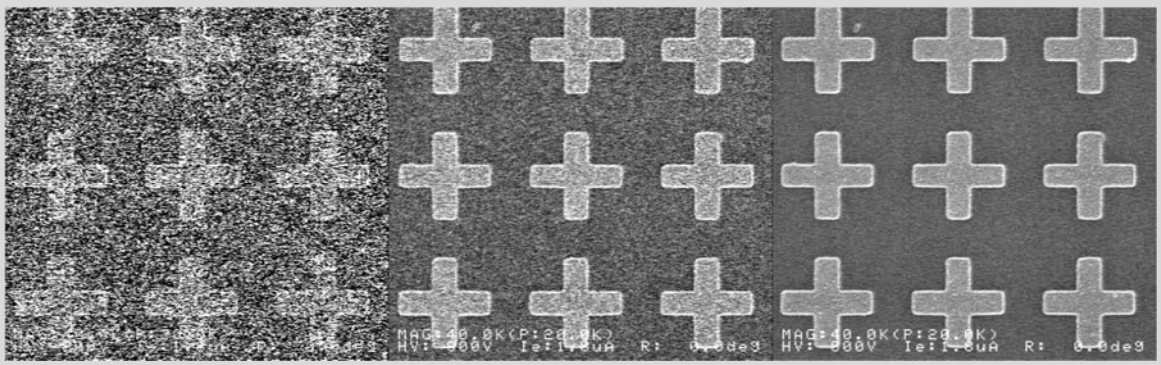
SEM Image Pixel Resolution



512 pixels 4096 pixels

Images with higher pixel density might provide more information, and reveal otherwise not perceivable features

SEM Signal-to-noise Ratio

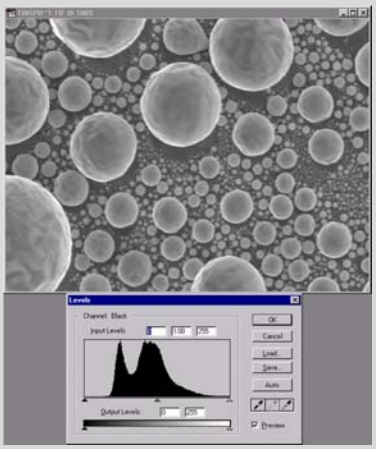


2 frames 8 frames 32 frames

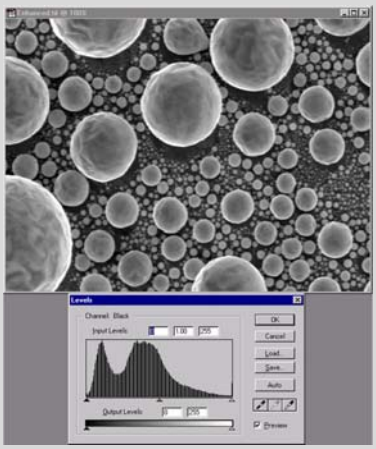
Acquiring images over longer time can improve the signal-to-noise ratio, and more details can be discerned.

Contrast Adjustment

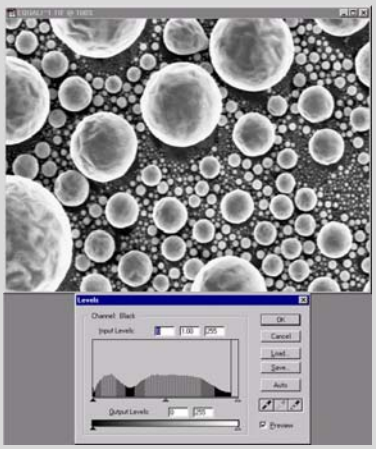
Original Image



Histogram Stretched

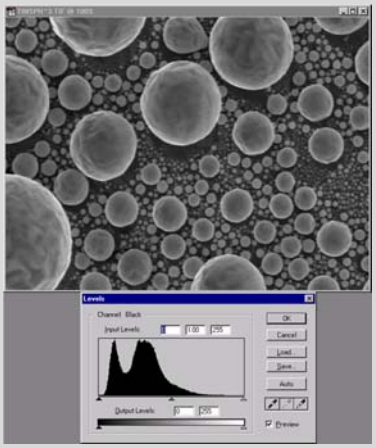


Histogram Equalized

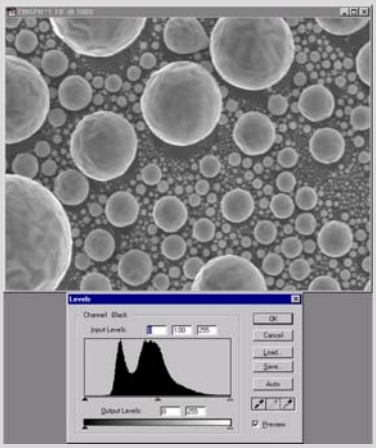


Brightness Adjustment

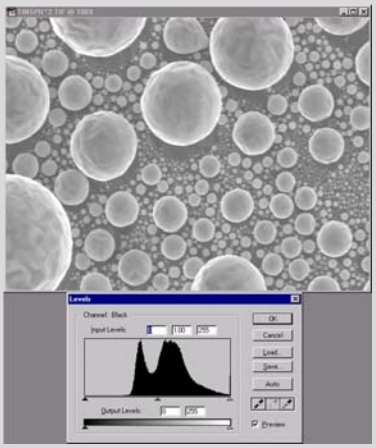
-35 gray levels



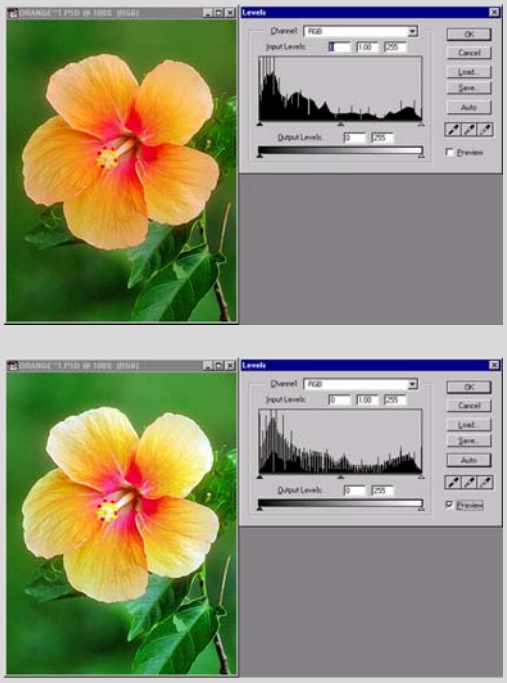
Original image

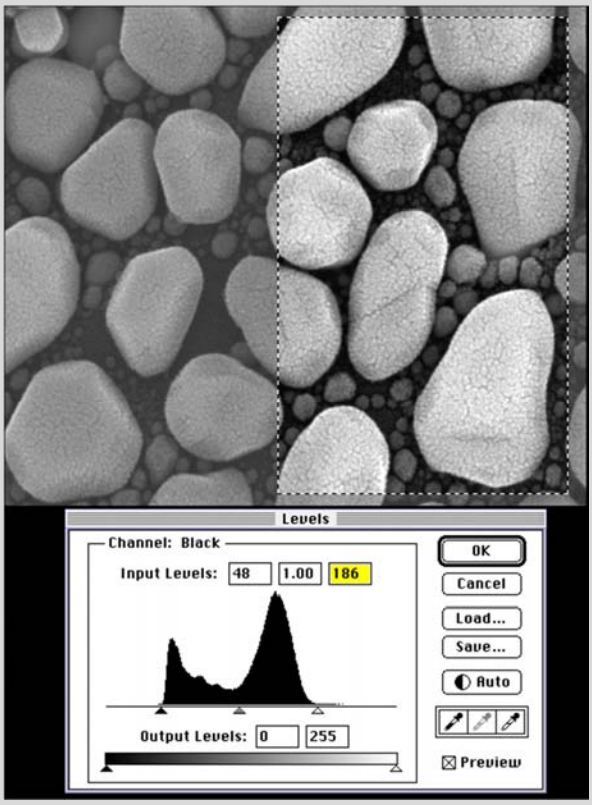


+35 gray levels

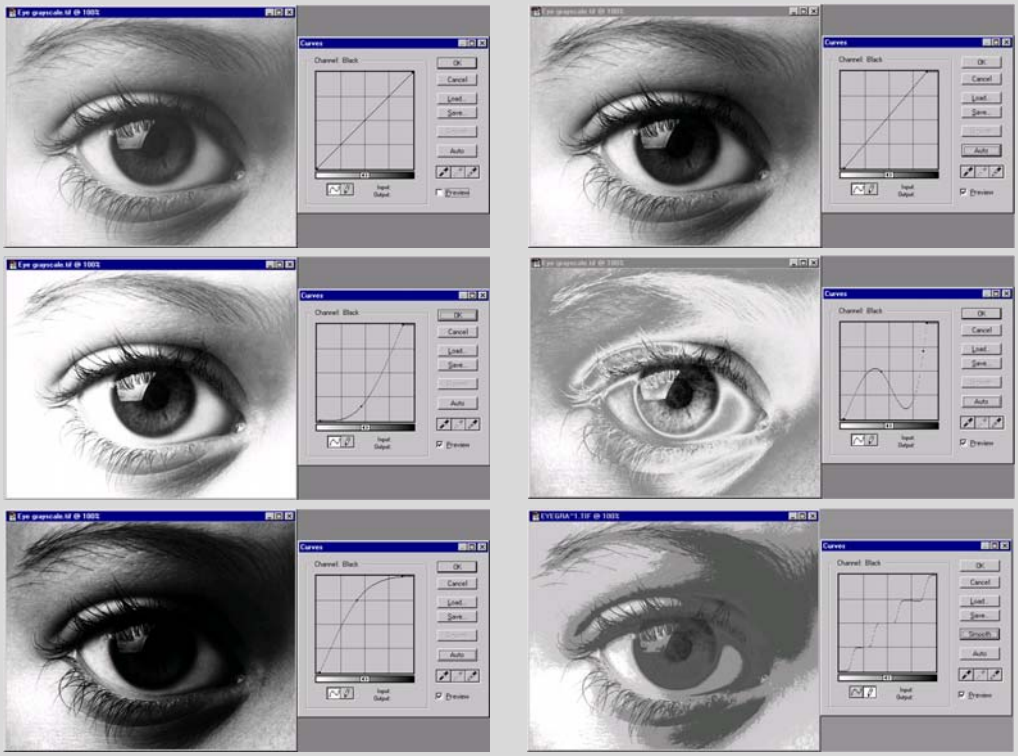


Histogram Stretch

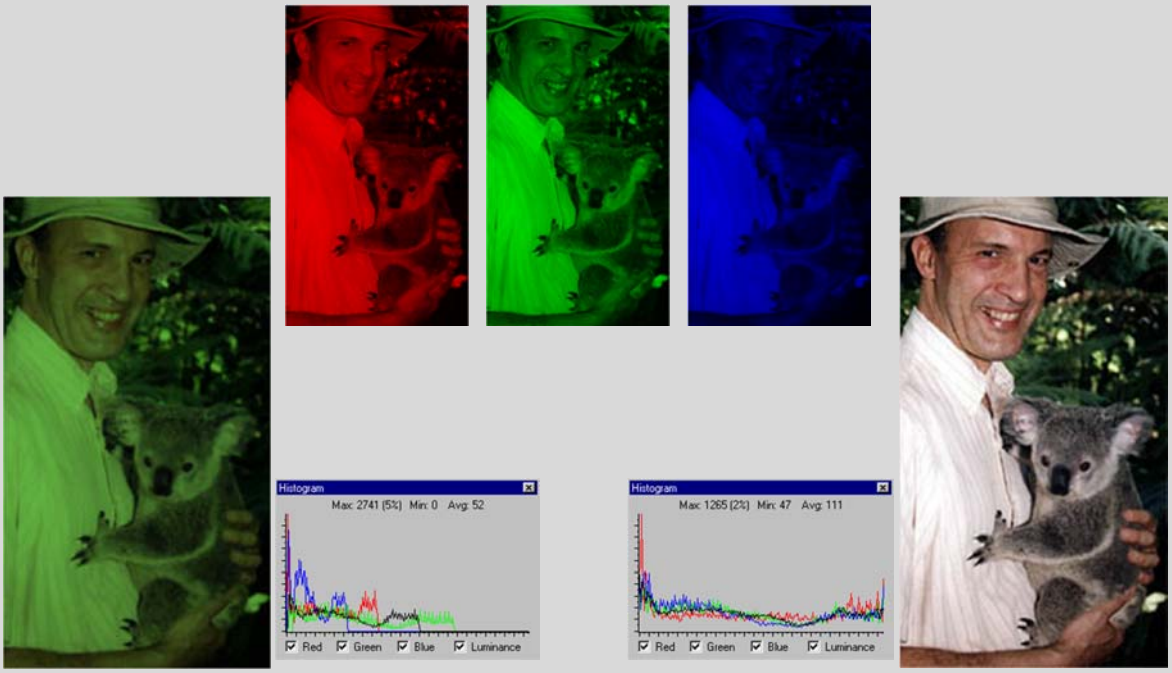




Histogram Adjustment - Transfer Function



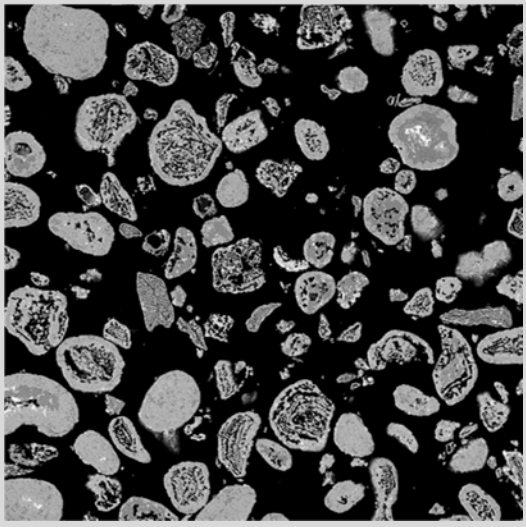
Fixing Colors with Histogram Adjustment



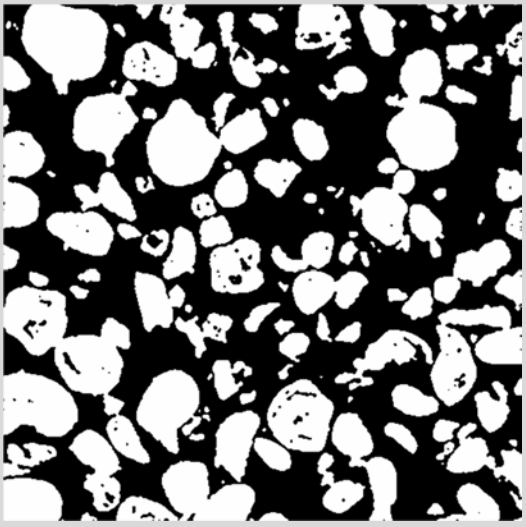
Original RGB images are from David Bright of NIST

From Images to Measured Data

Gray scale image

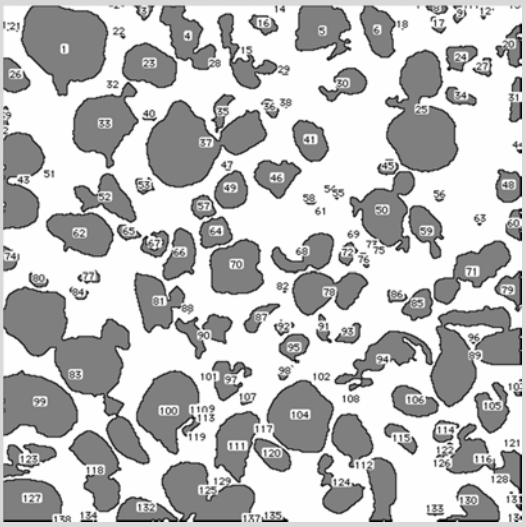


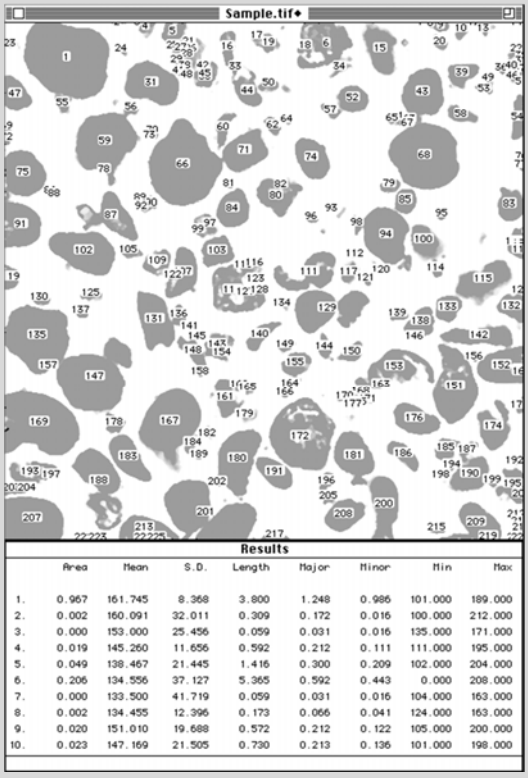
Binary version



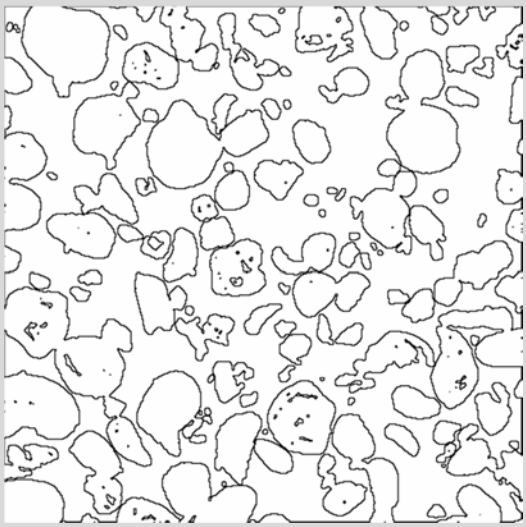
Analysis Result

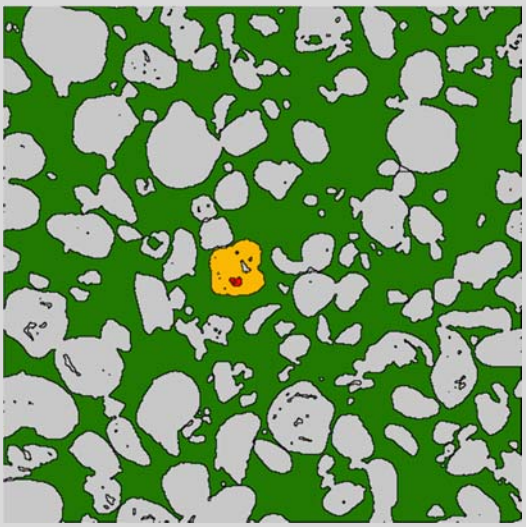
Particles



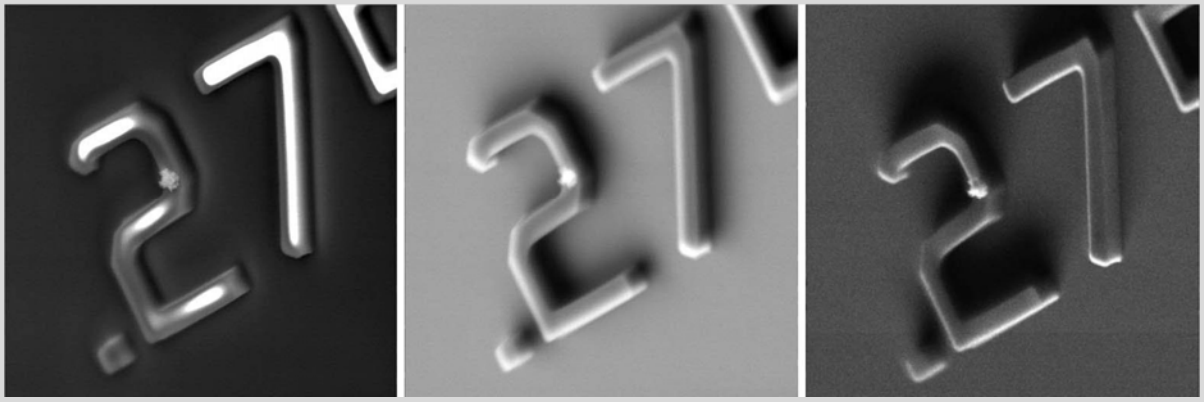


To Interpret Results: Human Mind Needed



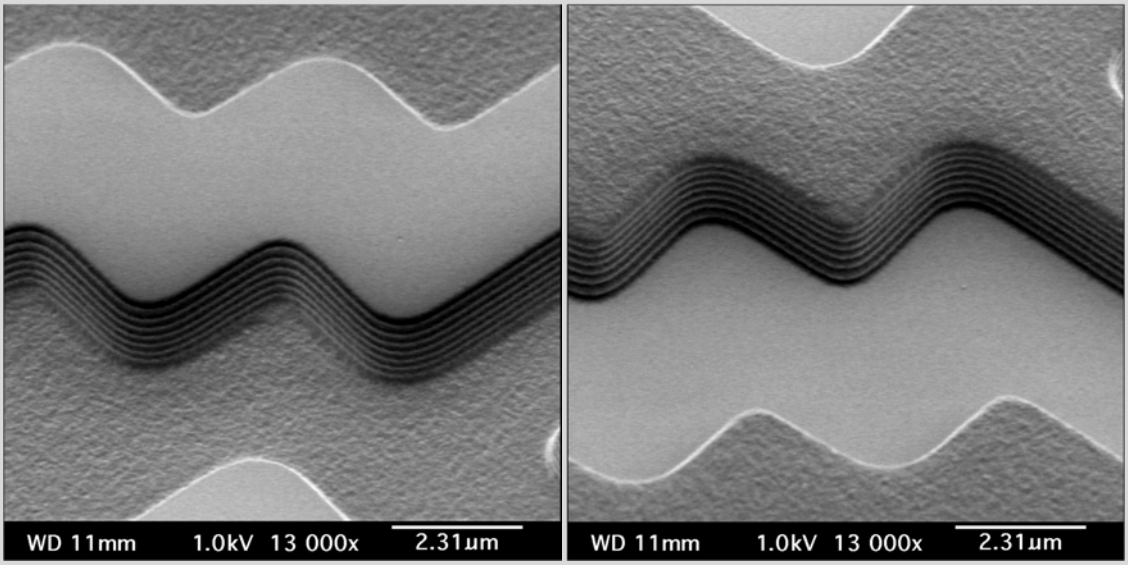


Which one is Right?

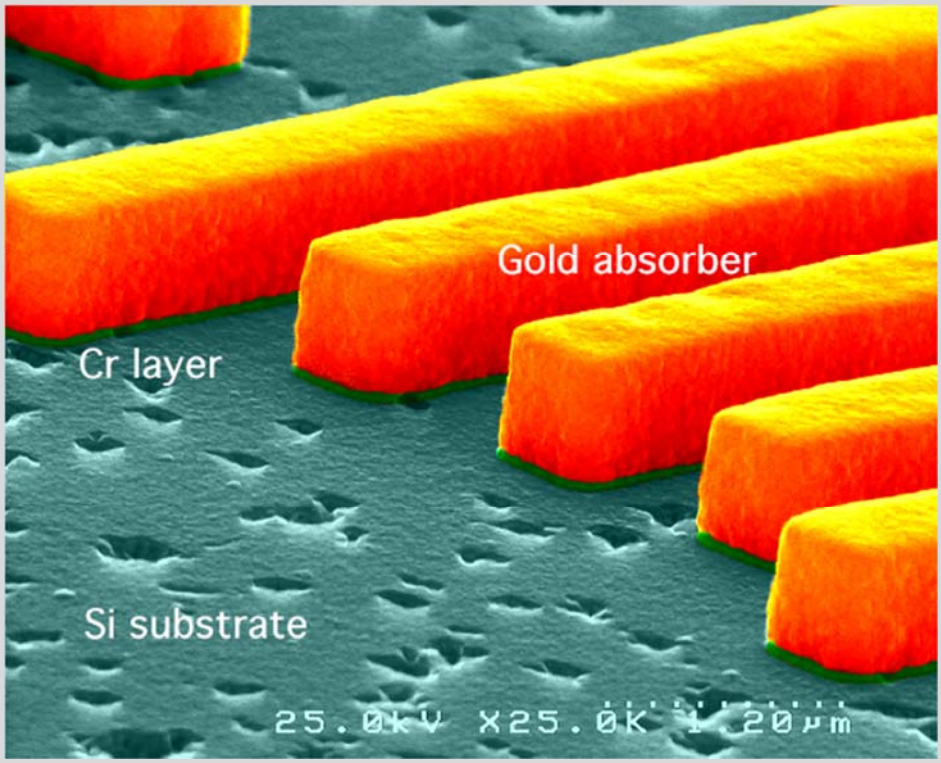


Same sample, different electron detectors upper SE, lower SE, low-loss BE

3D SEM? Which is Correct? In or Out?

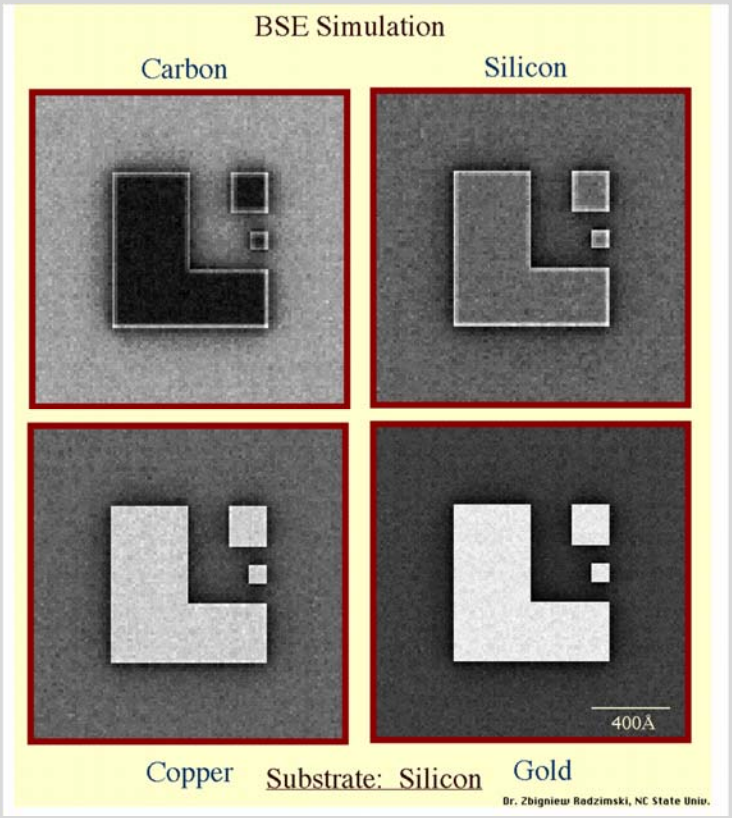


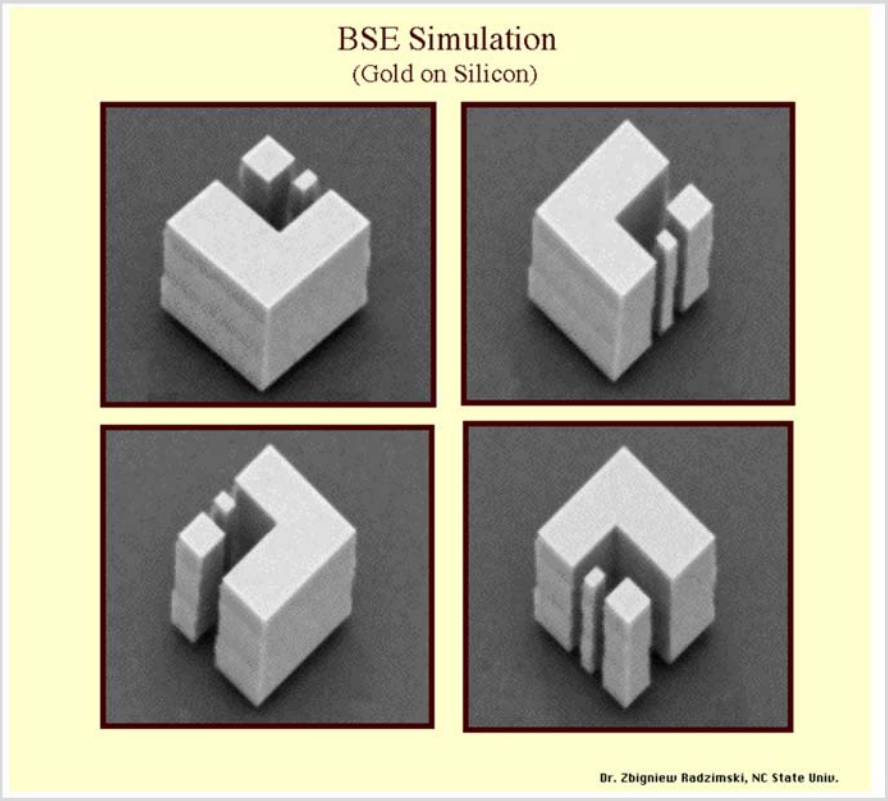
3D SEM? Color SEM?



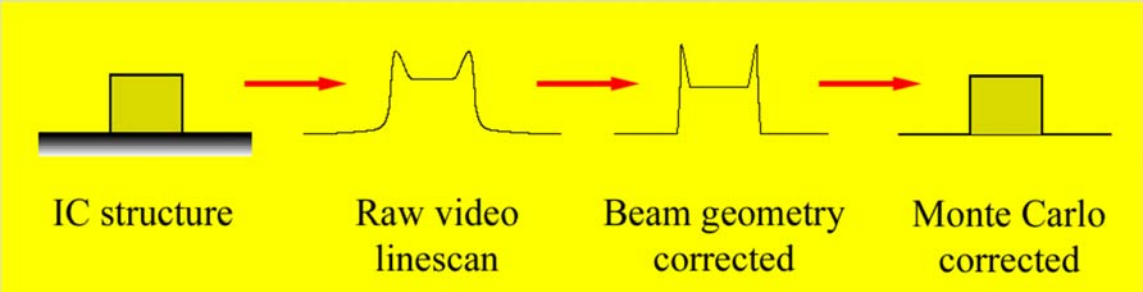
The Best Way to Interpret the Results

- The SEM images are not height maps of the sample
- Instead of various fudge factor calculations, it is better put science to work
- Monte Carlo modeling and simulation finds the necessary parameters to turn the intensity distribution into real sample geometry information
  - compensation for the geometry (edge, height, angle, etc.) and material contrast and charging
  - compute yield and trajectory changes of the SE & BE signal due to sample, sample chamber, detector and charging effects. Data Library
  - 3-D rendering


BSE Simulation
Carbon
Silicon
400Å
Copper
Substrate: Silicon
Gold
Dr. Zbigniew Radzimski, NC State Univ.


BSE Simulation
(Gold on Silicon)
Dr. Zbigniew Radzimski, NC State Univ.

From IC Structures to Correct Dimensions



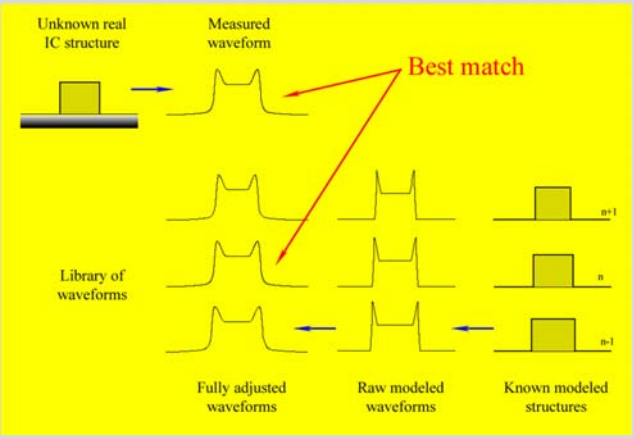
Correct SEM measurement

De-convolution

Model-based edge criterion

Library-based Dimensional Measurements

- The unknown integrated circuit structure can be measured by finding the best match chosen from a modeled library of possible shapes.
- This method is superior to any currently known and used algorithm



3-D SEM Imaging

SEM image pair → extraction of height and texture information → 3-D rendering

http://www.soft-imaging-web.de/

The Best of Scanning Electron Microscopes

- The SEM images provide rich information of samples over the millimeter to nanometer scale on a very large and diverse set of samples
- Thousands of SEMs are used in research, development and production
- 3D and super-high resolution imaging and measurements are becoming reality, so are inexpensive SEMs that can do most of the needed work
- For the most demanding applications expensive instruments and laboratories and knowledgeable microscopists are needed