

# *Nanomaterials: the Substance of Nanotechnology*

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*Rensselaer Nanotechnology Center  
Rensselaer Polytechnic Institute*



Briefing for the President's Council of Advisors on Science and  
Technology (PCAST), Washington, DC

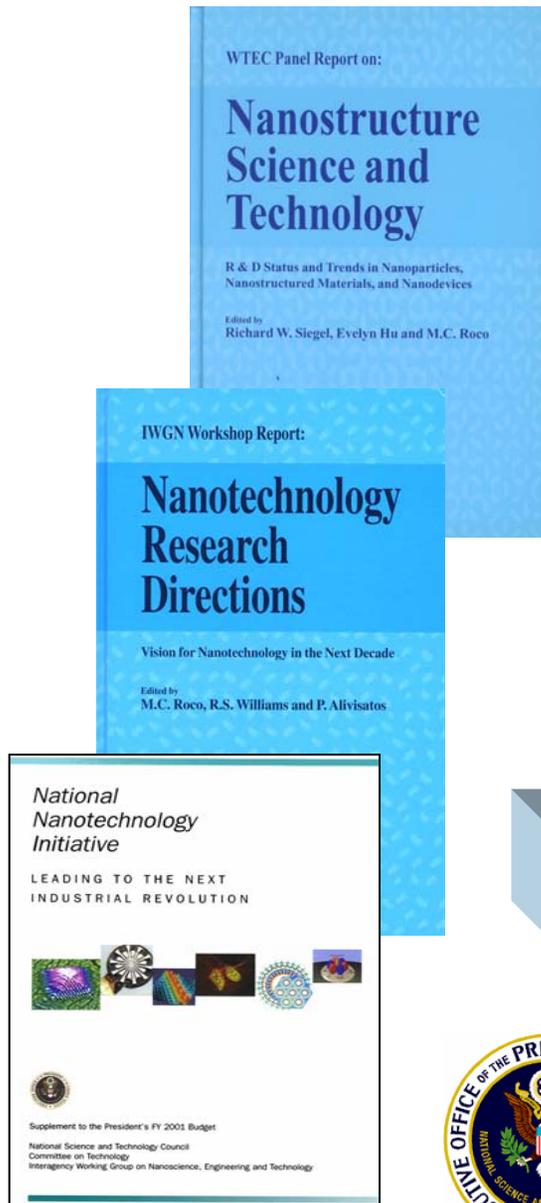
3 March 2003

*materials are needed to make  
anything in technology...*

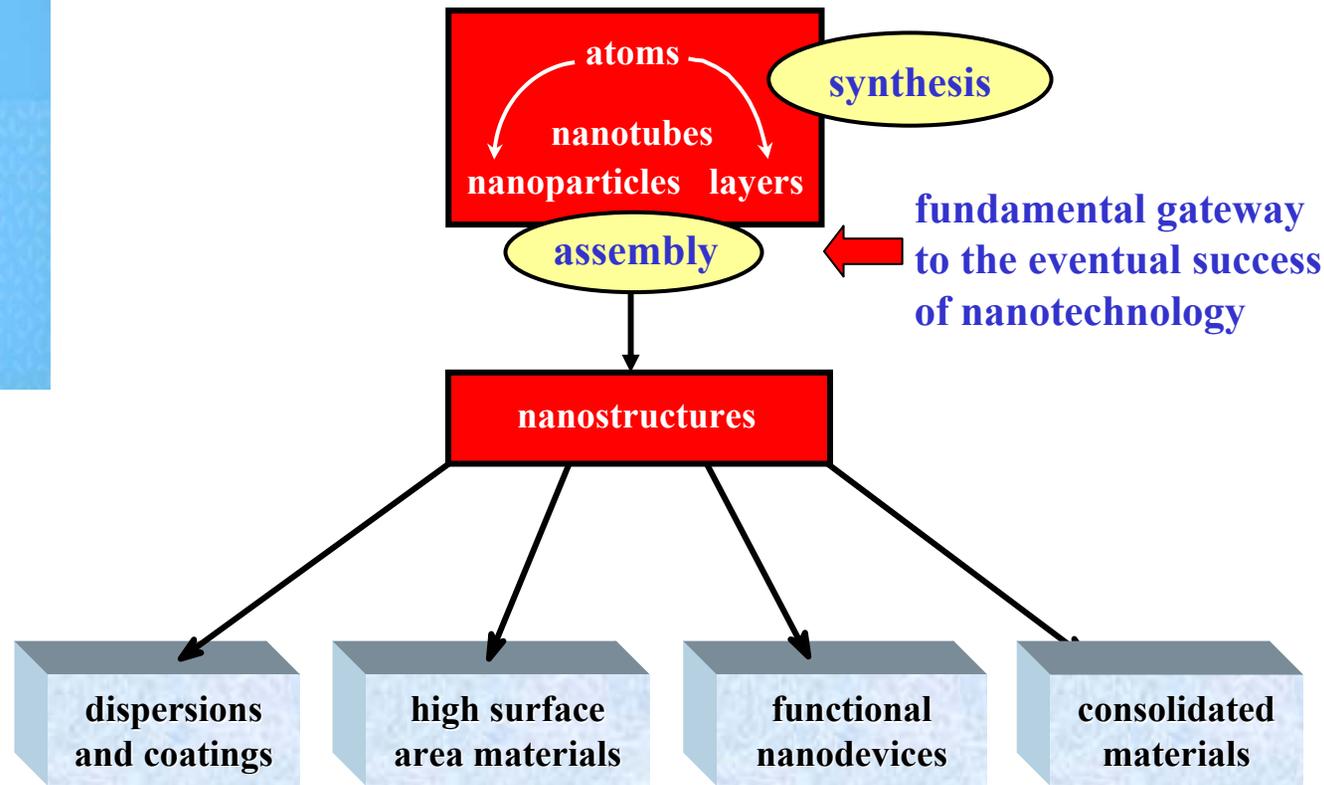
*nanomaterials are needed to make  
anything in nanotechnology*



# ...from atoms to applications through nanoscience



nanoscale building blocks



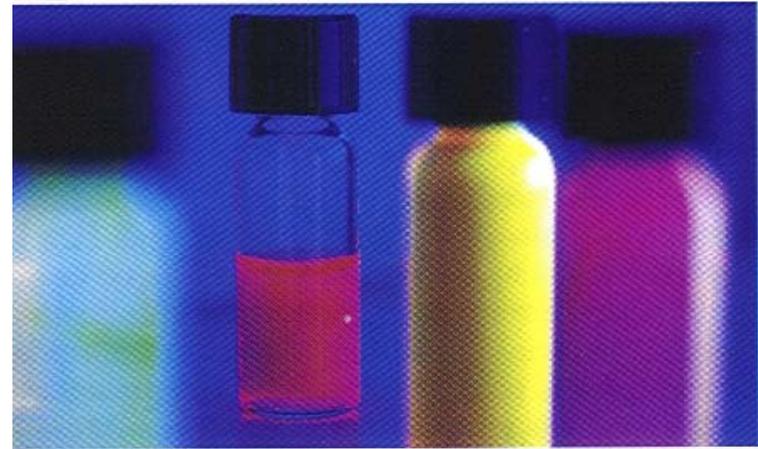
applications in our macroscopic world



<http://www.nano.gov/>

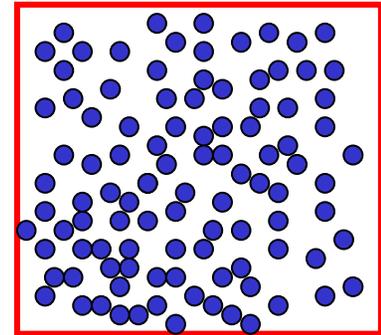
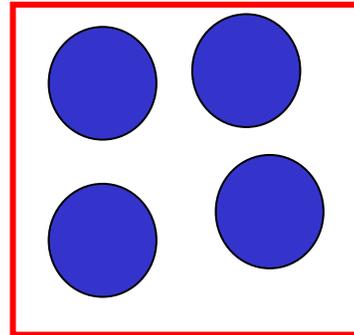
# What is special about nanoscale building blocks?

➤ **Size confinement**

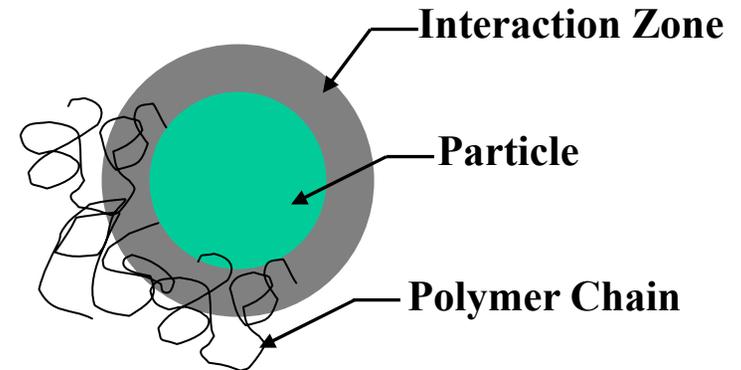
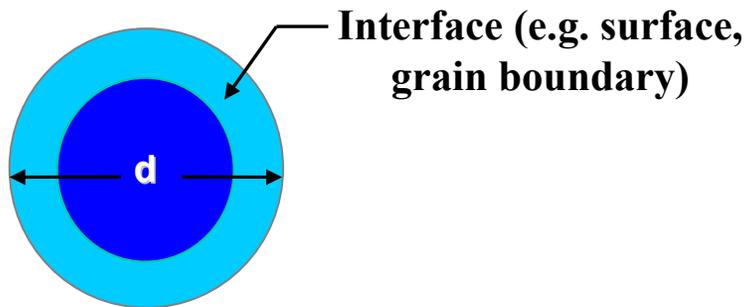
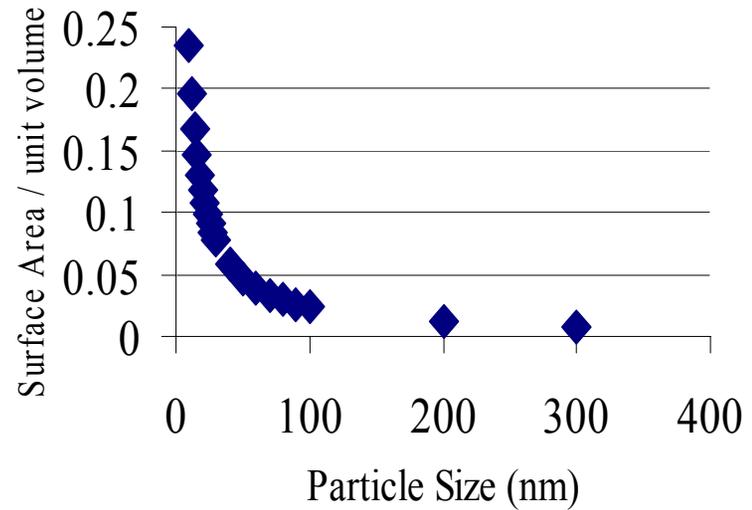
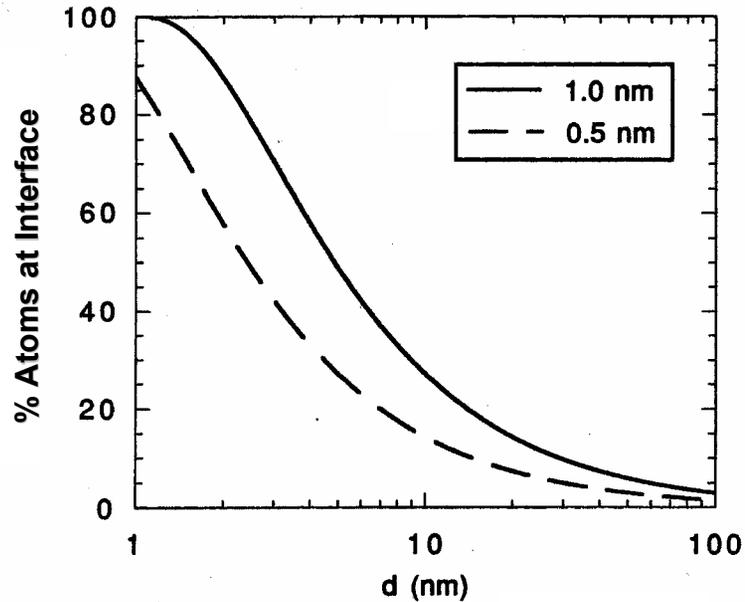


➤ **High surface area**

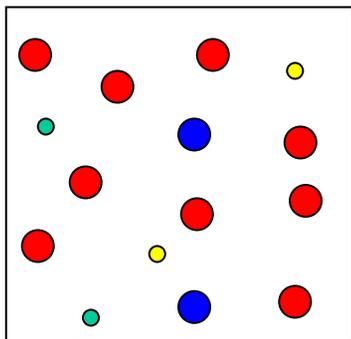
➤ **Many interfaces**



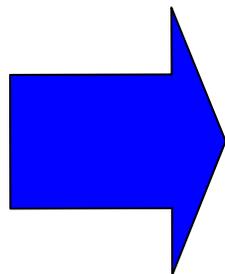
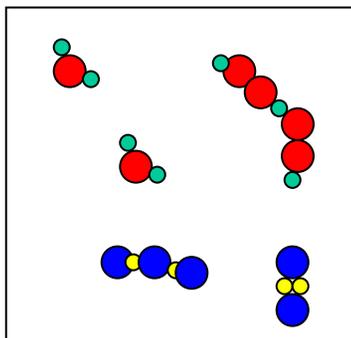
# Interface effects



## Atoms



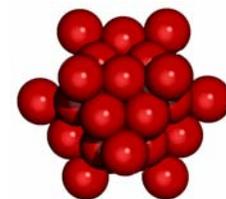
## Molecules



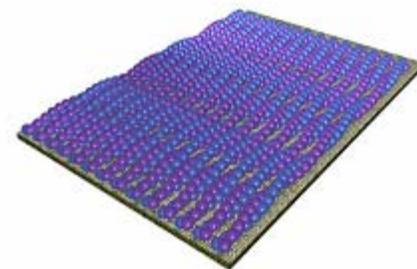
**Nanoscale  
building  
blocks**

1-100 nm

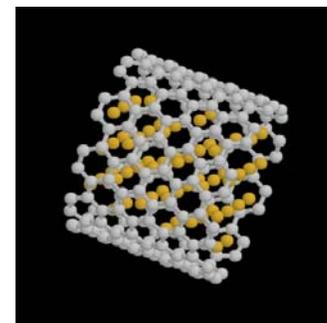
## Nanoparticles



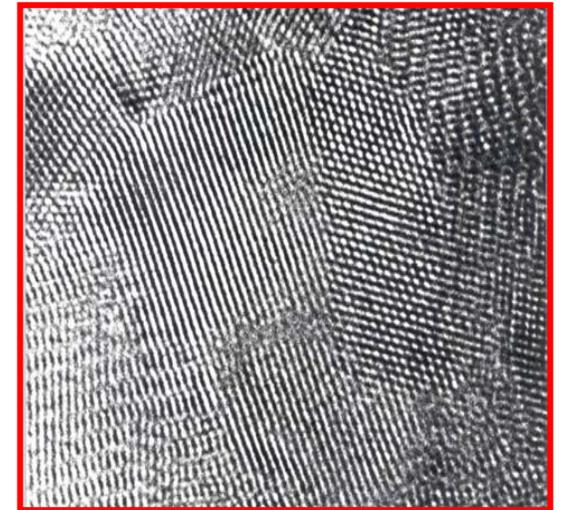
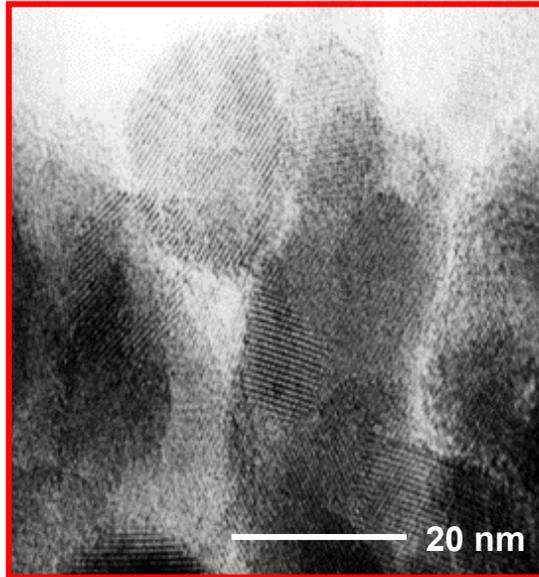
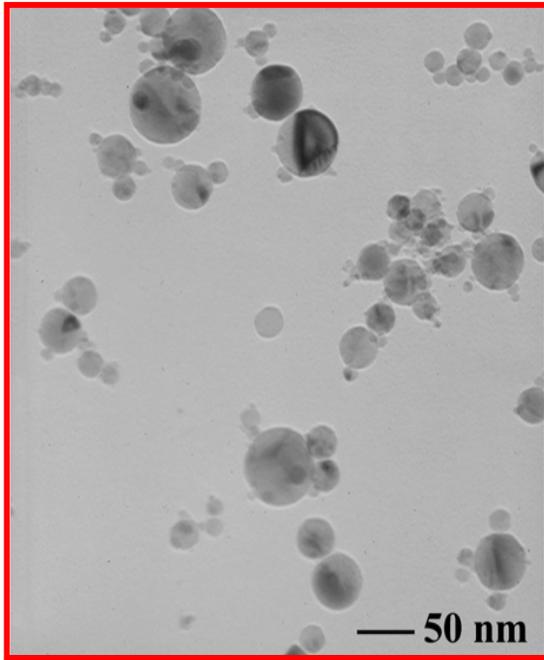
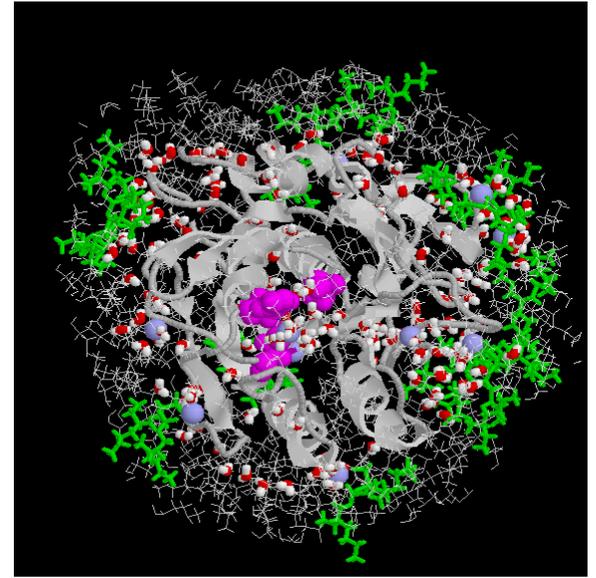
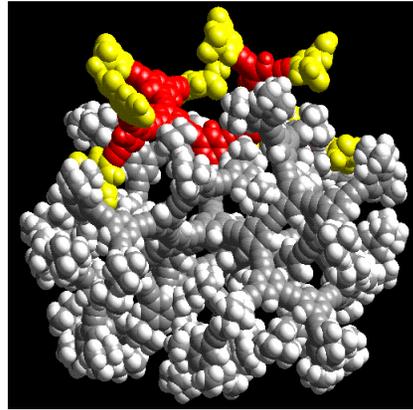
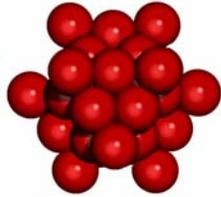
## Nanolayers



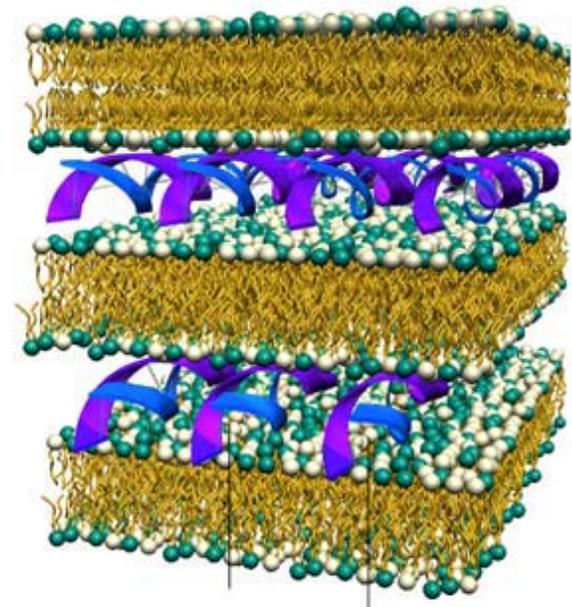
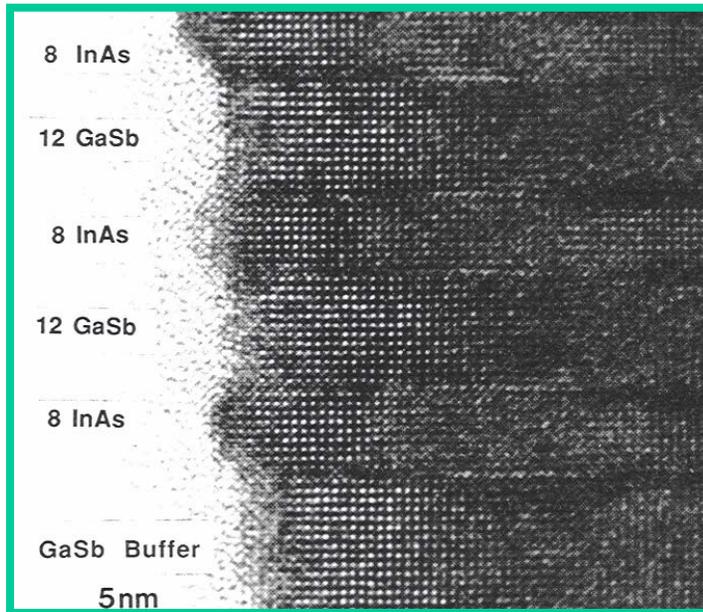
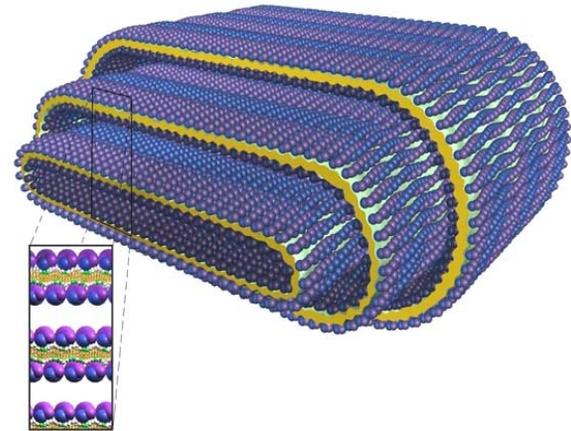
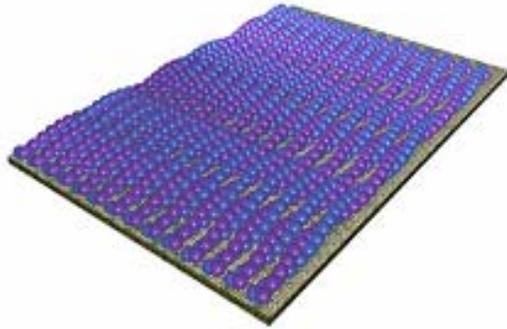
## Nanotubes



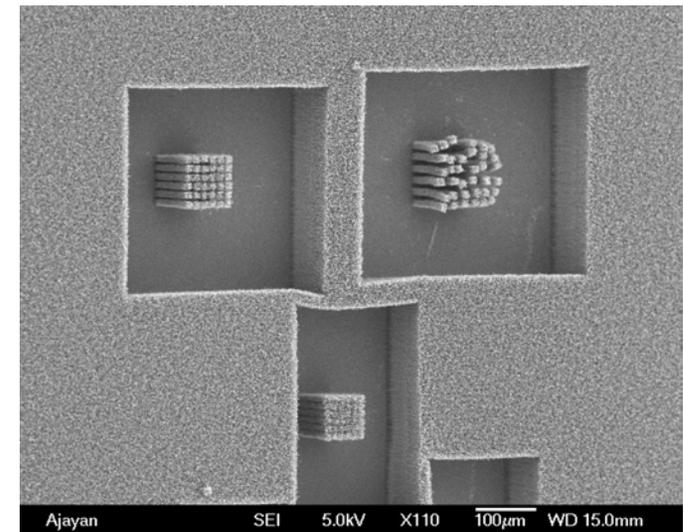
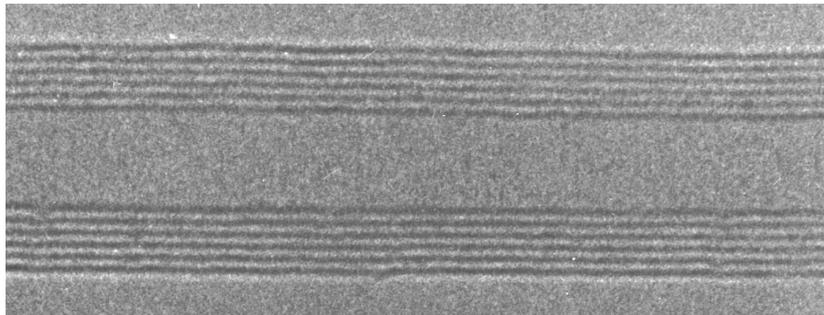
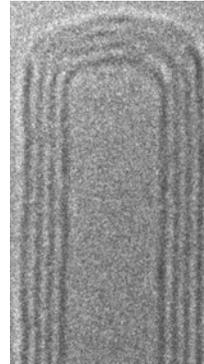
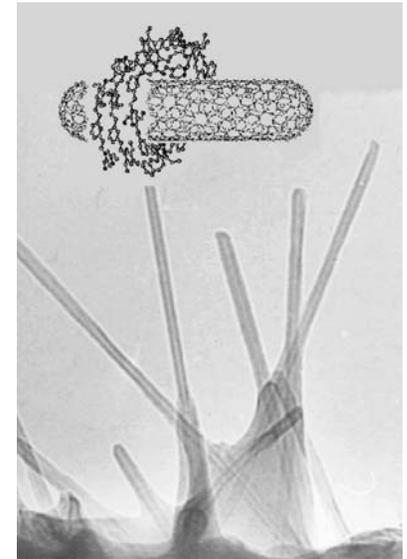
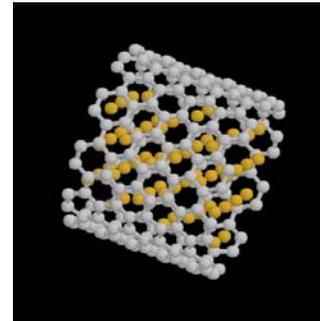
# Nanoparticles



# Nanolayers



# Nanotubes





# Characteristics of nanostructured materials and assemblies

- **Small**
- **Lightweight**
- **Novel properties**
- **Multifunctional**
- **Hierarchical**
- **Smart**



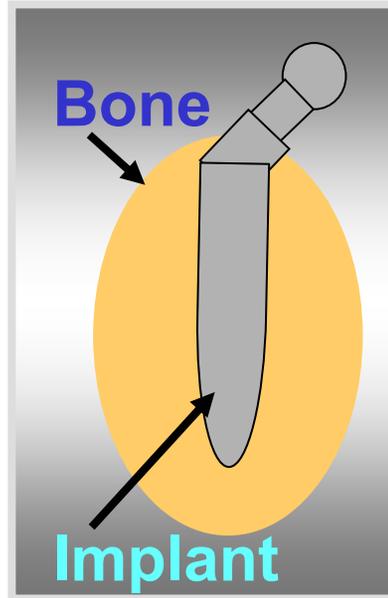
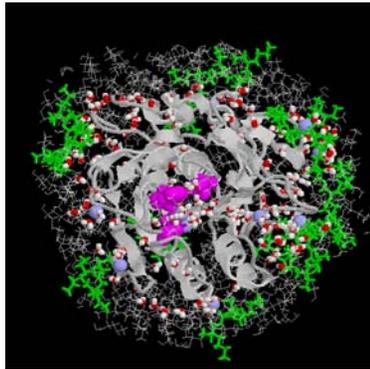
# Examples of opportunities for nanomaterials

- Thermal and environmental barriers
- Wear resistant coatings and parts
- Tailored optical and chemical barriers
- Flame retardant plastics
- High capacity energy and information storage media
- Drug and food supplement delivery vehicles
- Ultrahigh-strength, tough structural materials
- Net-shape formed ceramic parts
- Magnetic/thermoelectric thermal management devices
- Smart materials with embedded sensors and actuators
- Biomaterials

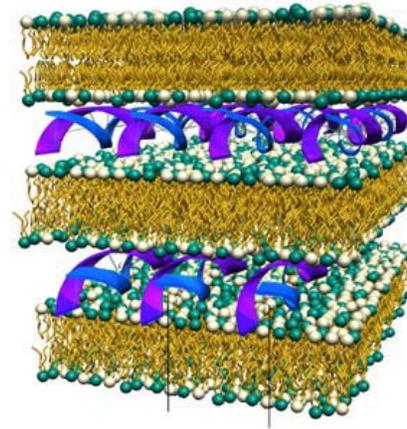


# Application areas

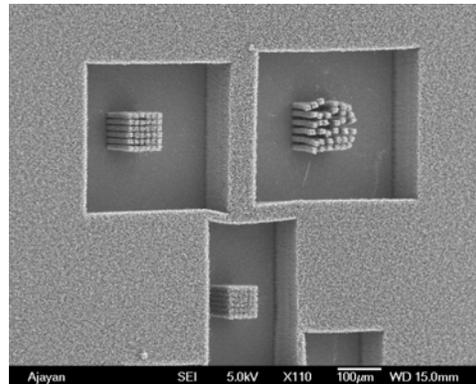
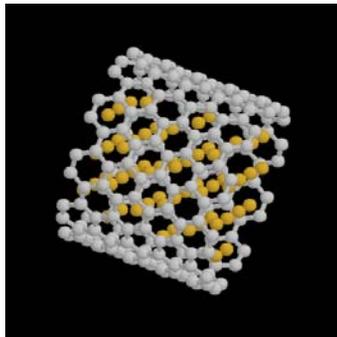
## Health



## Environment



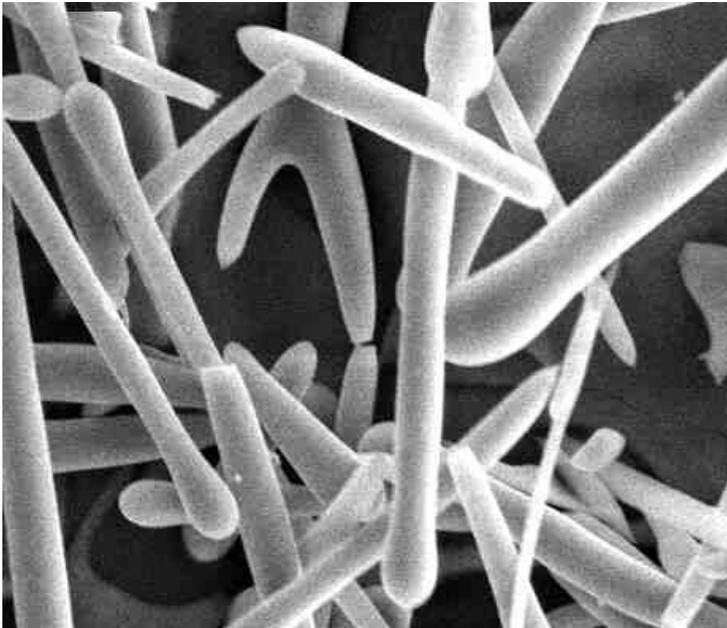
## Communication



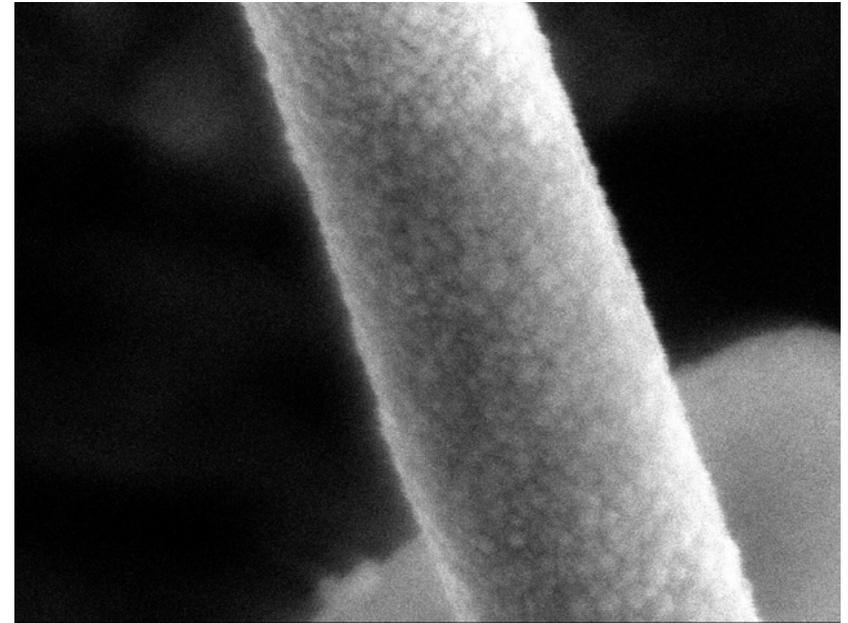
## Manufacturing



# Nanoparticle-assembled TiO<sub>2</sub> capped microtubes



6  $\mu\text{m}$



350 nm

*Ma, Siegel, Schadler (2002)*

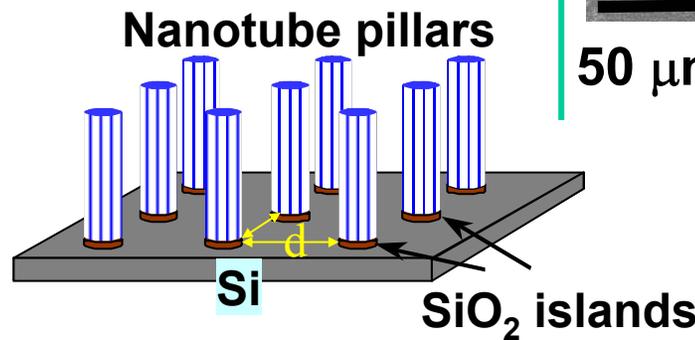
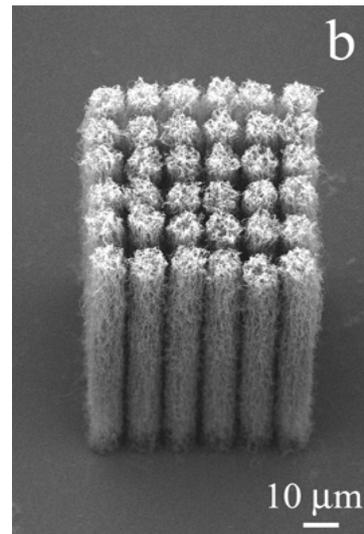
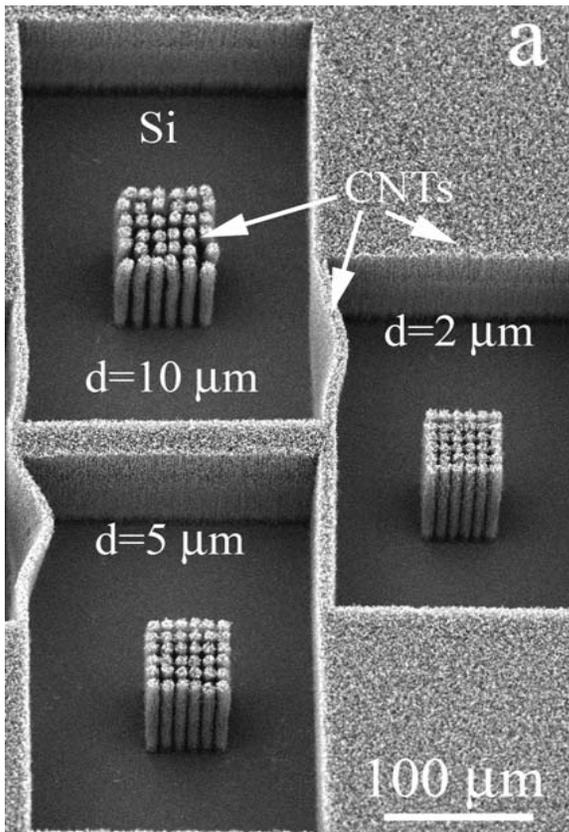
**ABB**



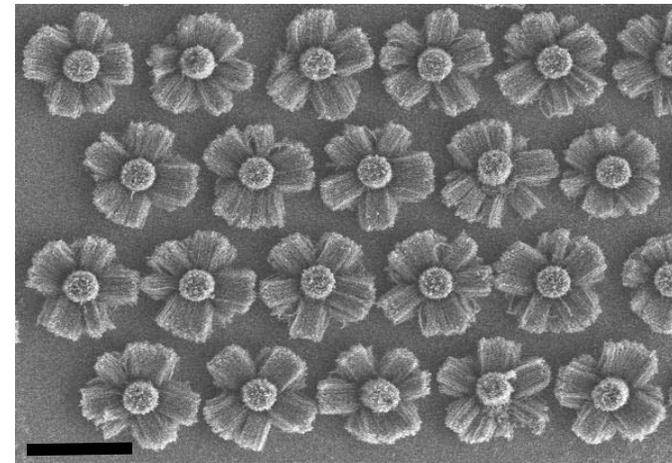
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# Controlled assembly of vertical interconnects: nanotubes



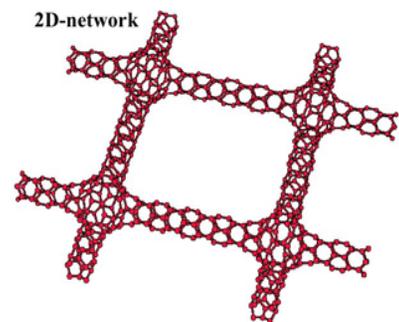
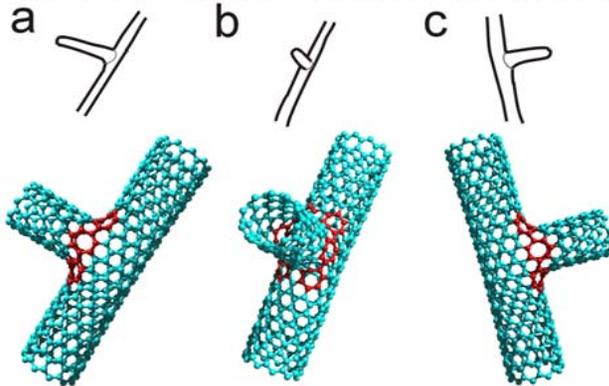
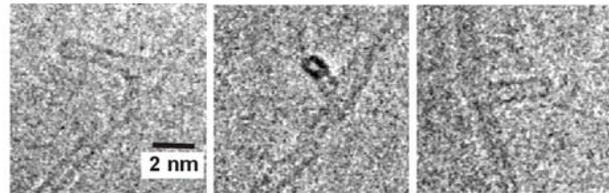
## Vertical and Horizontal



$50\ \mu\text{m}$

*Wei, Vajtai, Jung, Ward, Zhang, Ramanath, Ajayan (2002)*

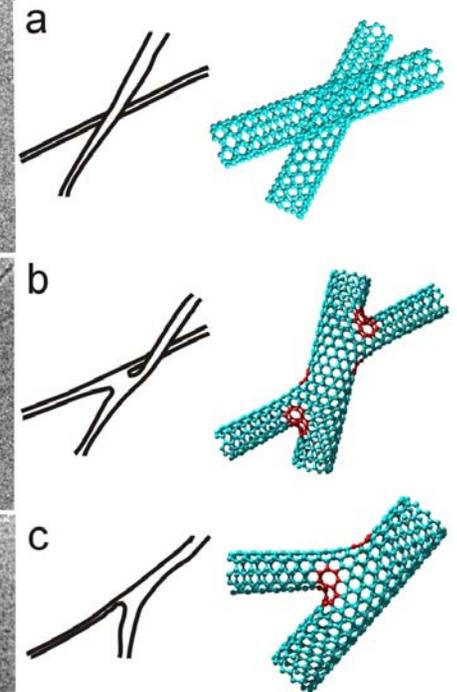
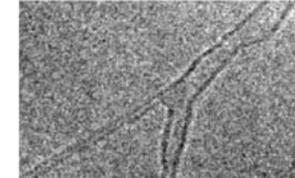
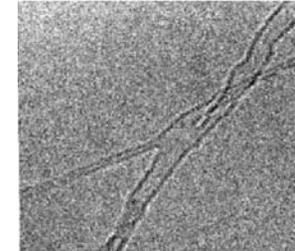
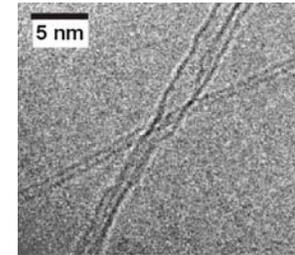
# Creating single-walled nanotube junctions



e-beam  
welding



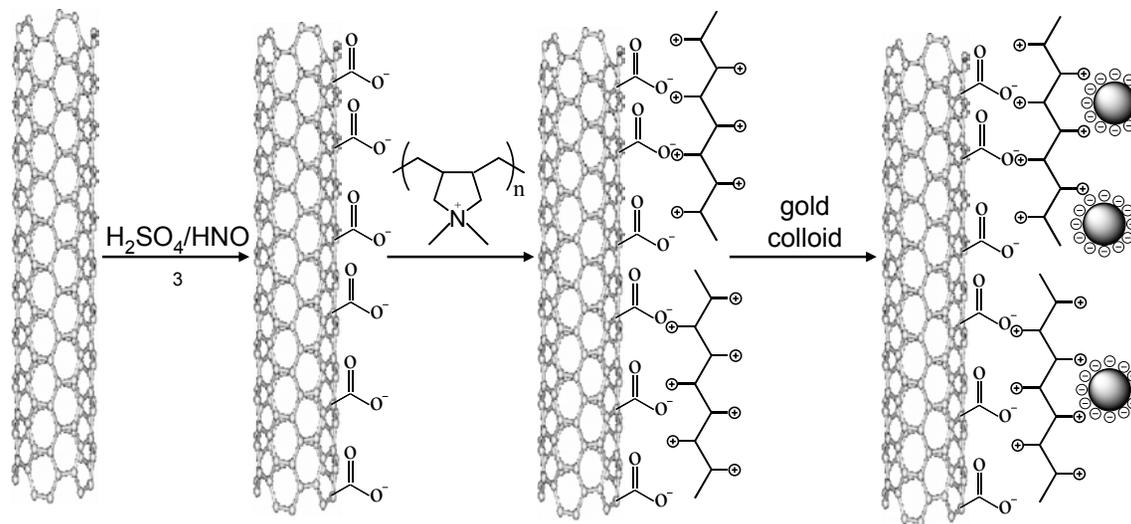
Future



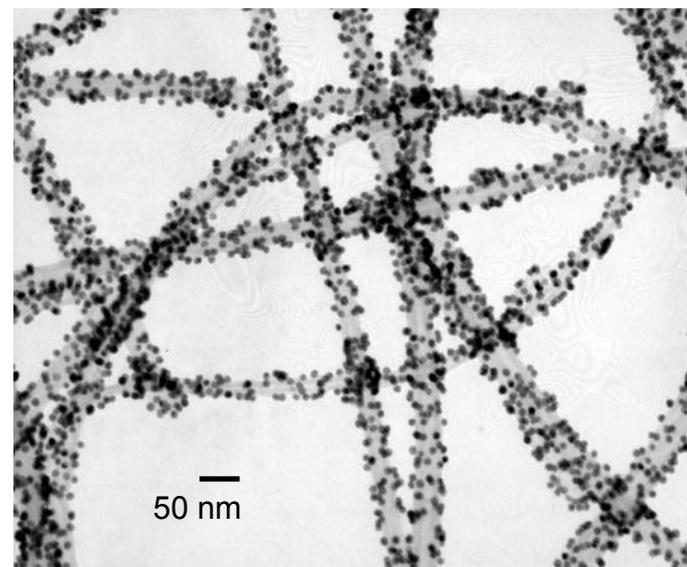
*Terrones, Banhart, Ajayan et al. (2002)*

Funded by the MARCO Interconnect Focus Center

# Attachment of Au nanoparticles to N-doped CNT



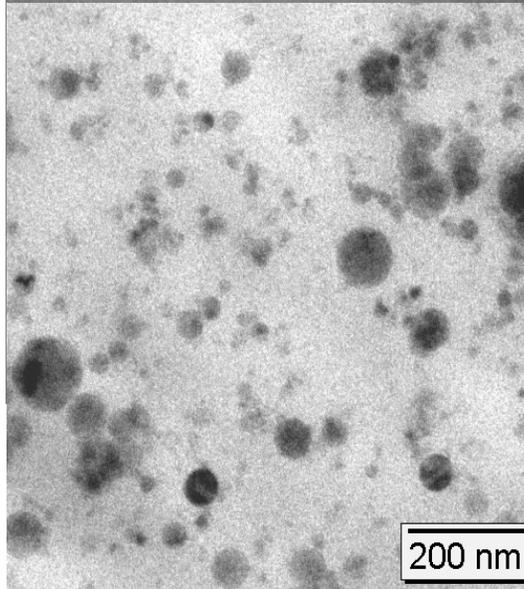
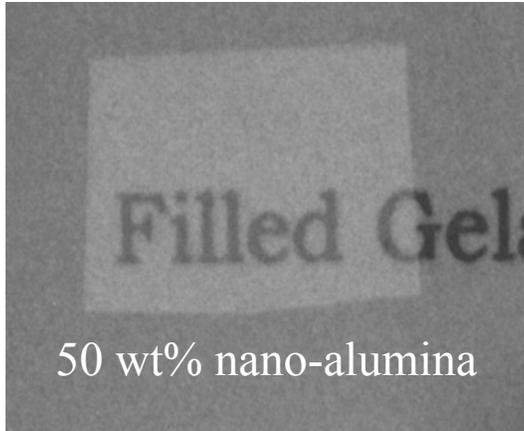
Functional groups are attached along the lengths and ends of N-doped carbon nanotubes (CNT). These become the sites for selective Au nanoparticle attachment.



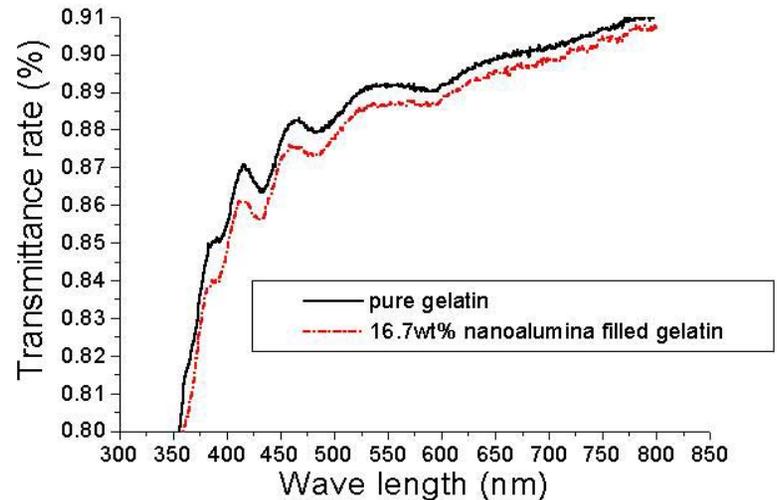
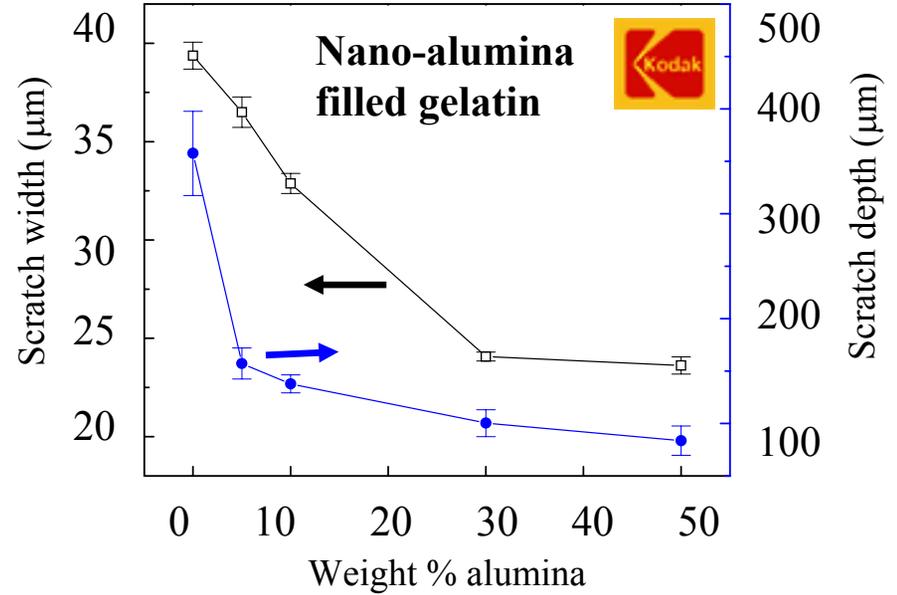
*Jiang, Eitan, Schadler, Ajayan, Siegel, et al. (2002)*

Funded by US Army Natick Soldier Center

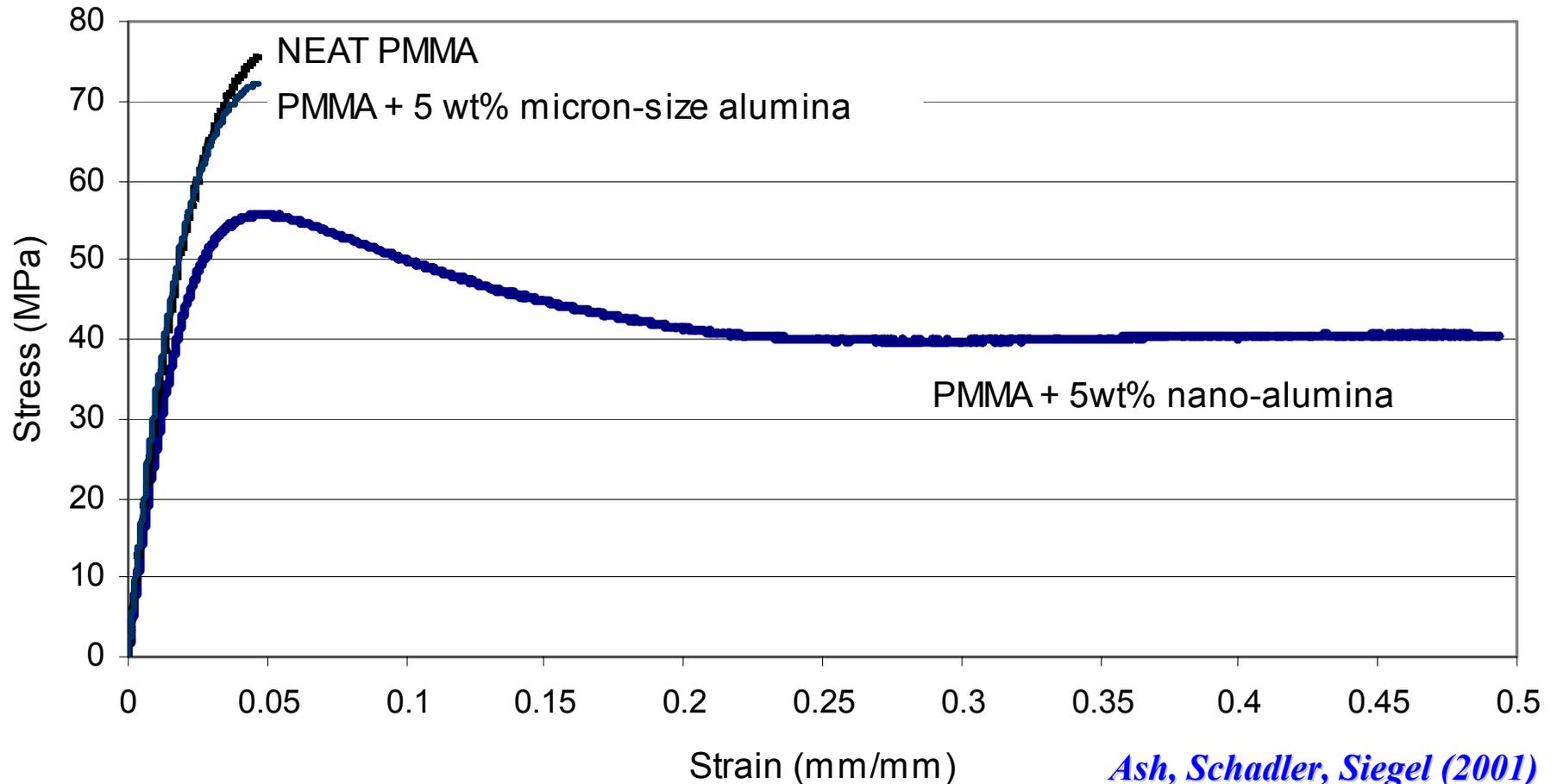
# Polymer nanocomposites - assembly and properties



16.7 wt% nano-alumina



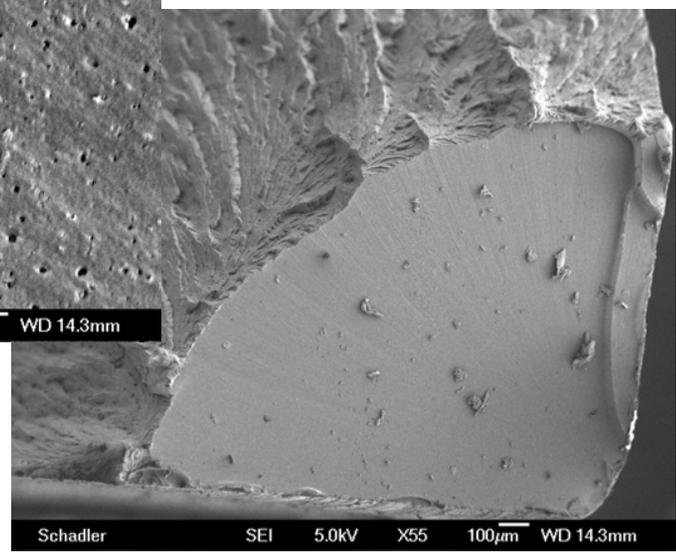
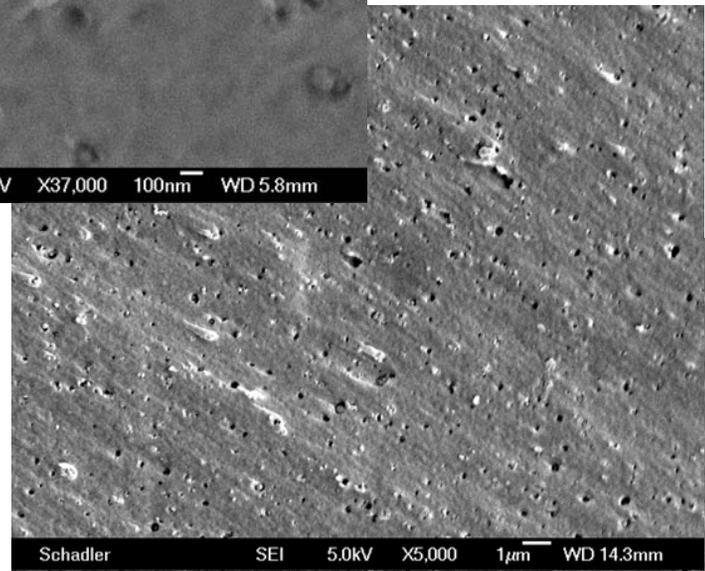
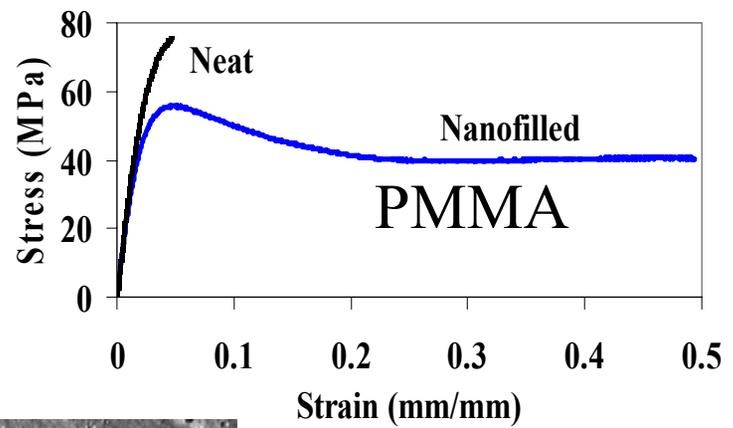
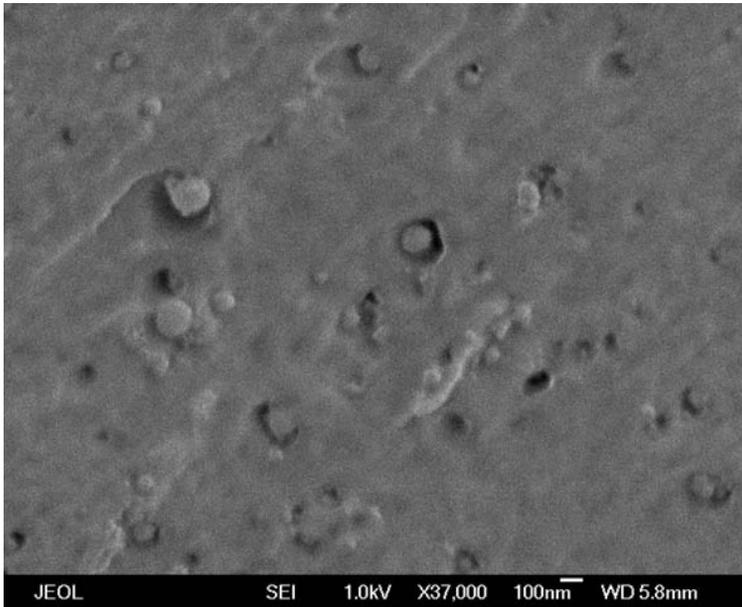
# Comparison between micron-size and nanoscale alumina fillers in PMMA



*Ash, Schadler, Siegel (2001)*

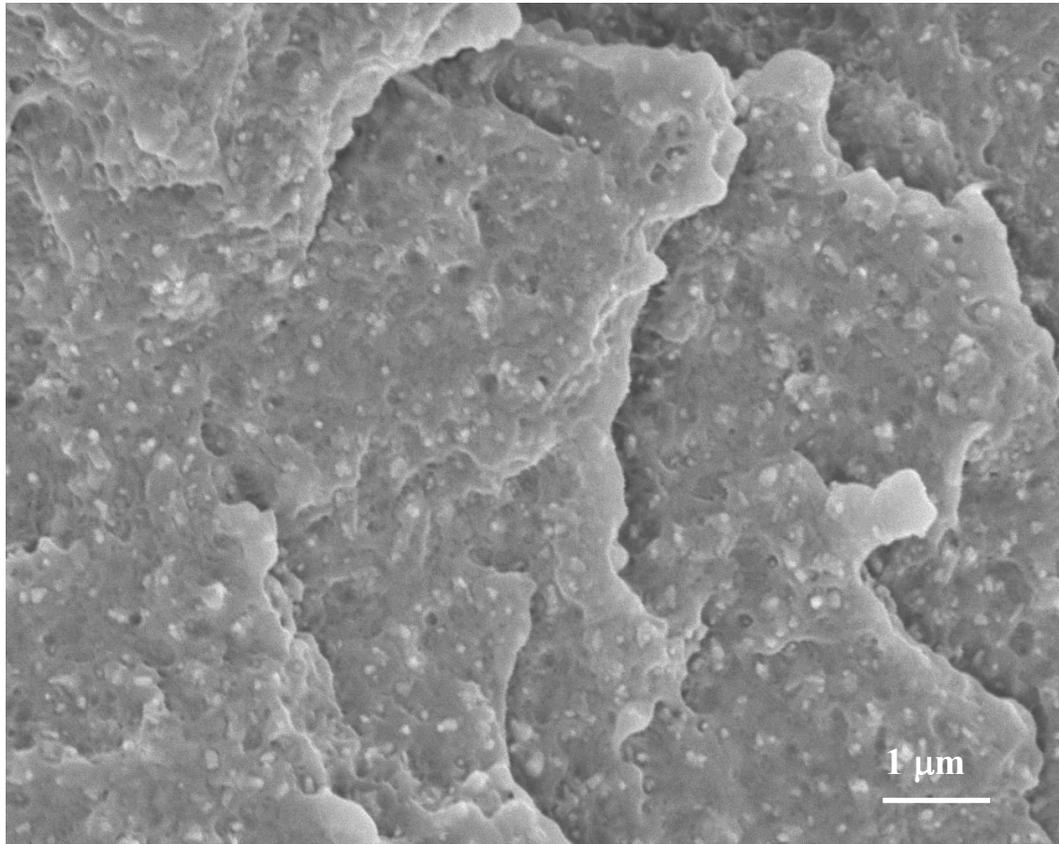


# PMMA/alumina fracture surfaces by FESEM



*Ash, Schadler, Siegel (2002)*

# ZnO/LDPE nanocomposites



SEM of 50 wt% ZnO in LDPE

*Hong, Schadler, Siegel, Mårtensson (2002)*

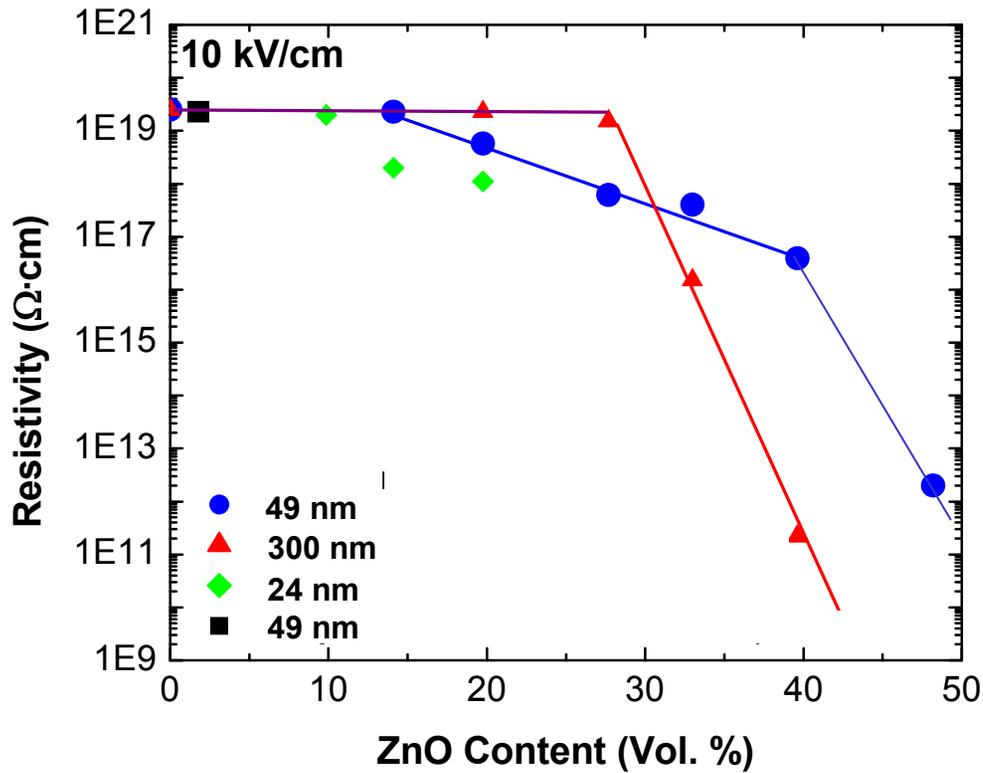
**ABB**



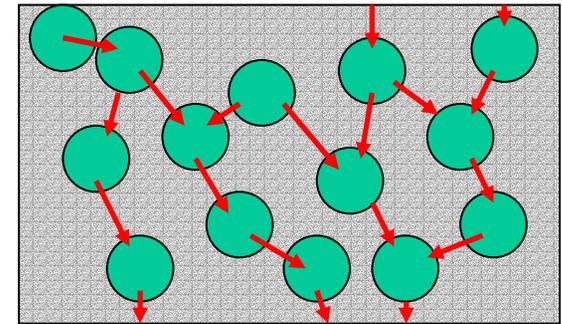
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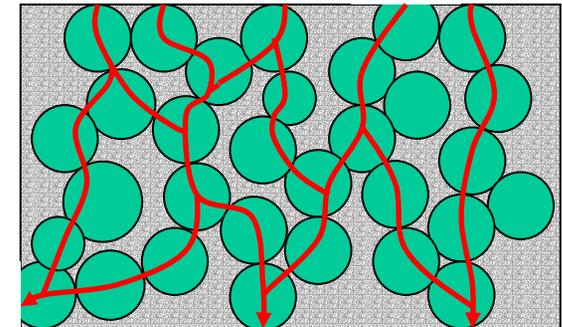
# Resistivity of ZnO/LDPE nanocomposites



Conduction mechanisms:



Tunneling



Continuous paths

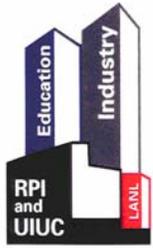
*Hong, Schadler, Siegel, Mårtensson (2002)*

**ABB**



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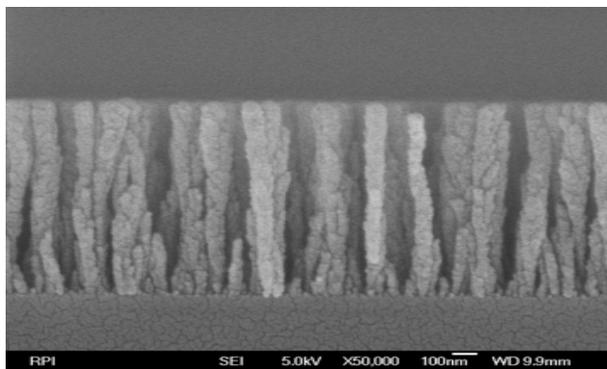
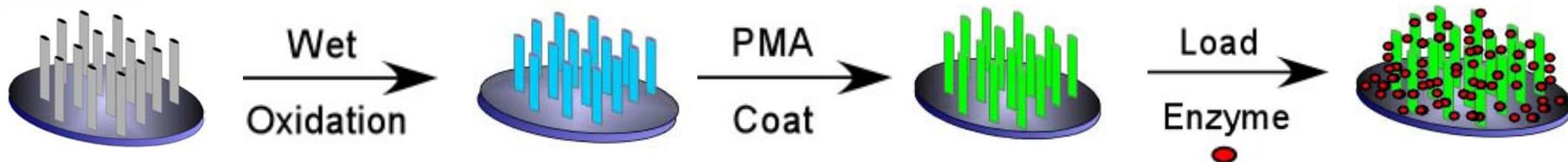
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## Potential applications of biocatalytic nanocomposites

- Catalysts
- Chromatographic packings
- Biocatalytic membranes
- Non-fouling coatings and paints
  - Protein, lipid, polysaccharide resistant
  - Microbial resistant
  - Sessile invertebrate resistant
- Non-clogging drain pipes
- Implantable medical devices
- Microelectronics and microfabrication

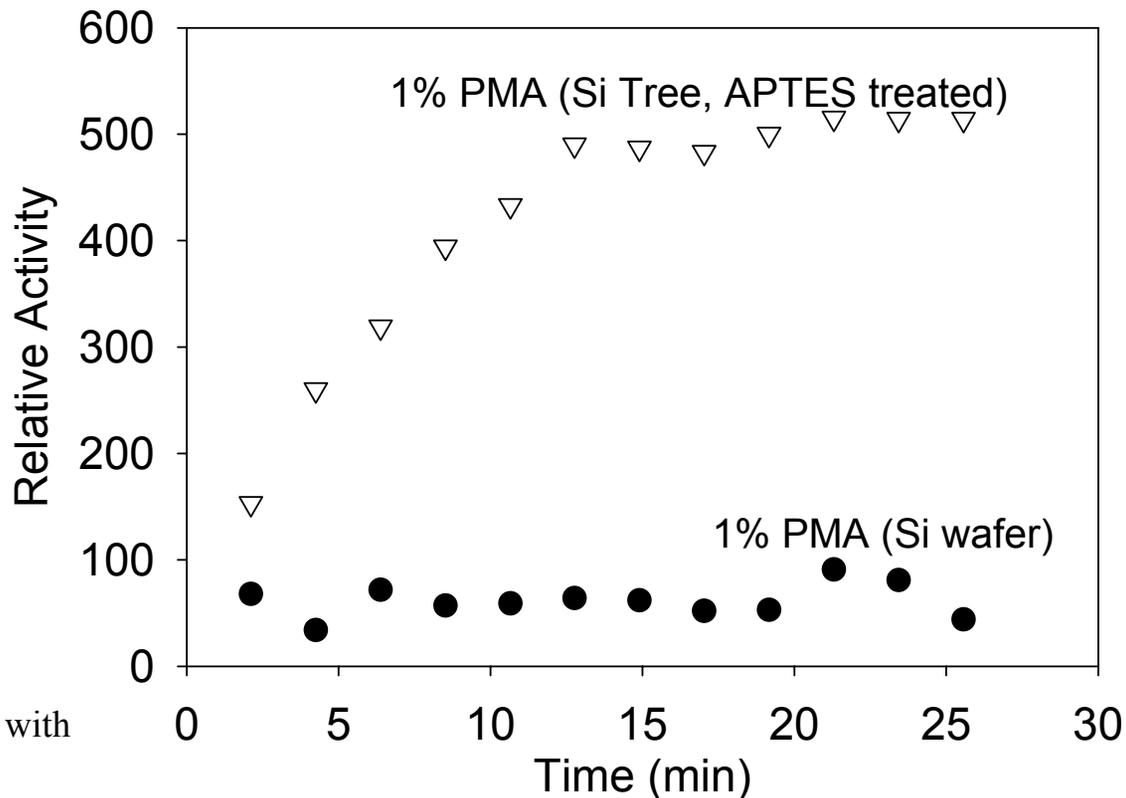
# Preparation and use of peroxidase-silicon nanocomposites



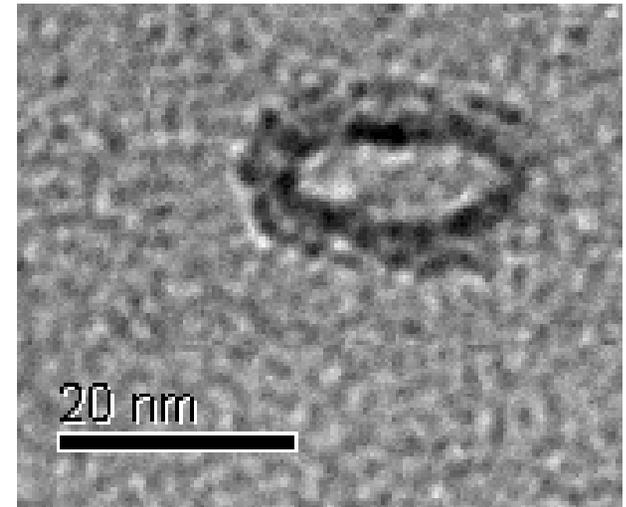
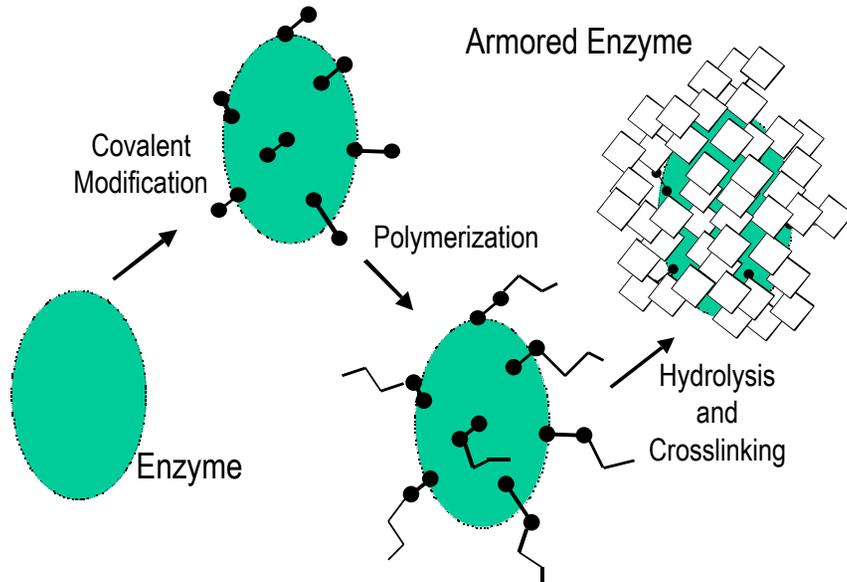
*Dordick et al. (2002)*

**Enzyme:** Soybean Peroxidase (SBP)

**Assay:** *p*-cresol [40 mM] in phosphate buffer with 20% DMF, H<sub>2</sub>O<sub>2</sub> [0.13 mM]

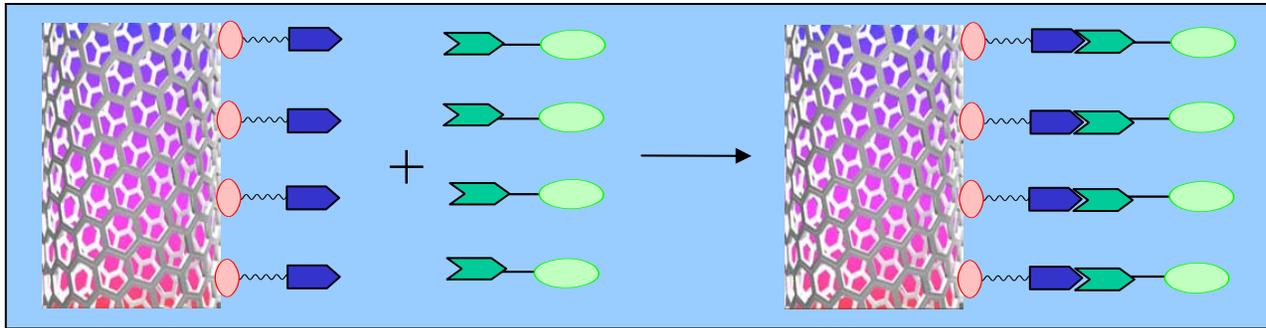


# Silicate-based “armored” enzyme nanocomposites

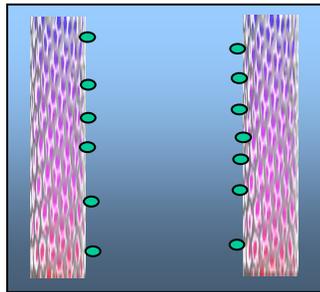


Preparation	$\tau_{1/2}$ (days)
Free $\alpha$ -chymotrypsin	0.01
Sol-Gel entrapped $\alpha$ -chymotrypsin	0.29
Armored $\alpha$ -chymotrypsin composite	358

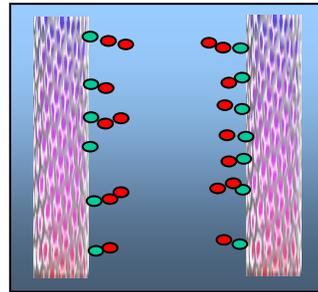
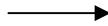
# Exploiting enzymes for structured polymer growth and membrane applications on nanotubes



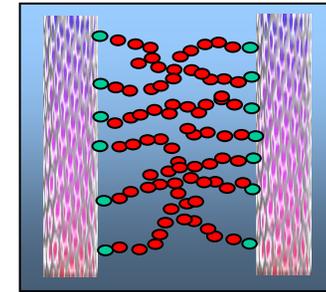
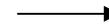
## *Polyhydroxyalkanoate synthesis with different monomers*



**Immobilized PHA pathway**



**Growing polymer network**



**Controlled membrane properties within NT network**

- ◆ Create controlled environments from templated nanotubes
- ◆ Assemble nanotube architectures from biopolymer linkers

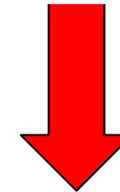
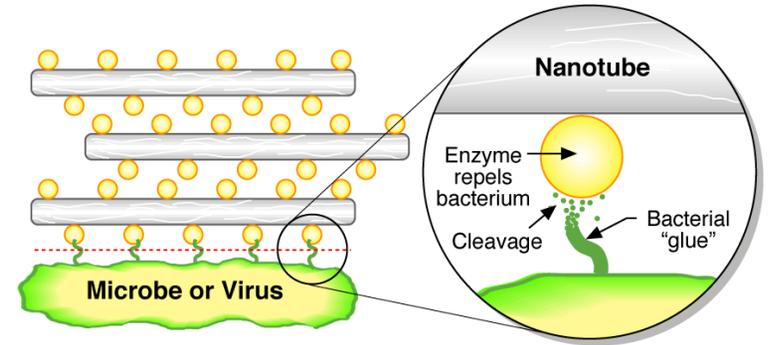
# Adaptable nanostructures that self clean and detoxify

Long-term opportunities:

- ◆ Anti-microbial surfaces →
- ◆ Anti-fouling surfaces
- ◆ Nerve gas detoxification

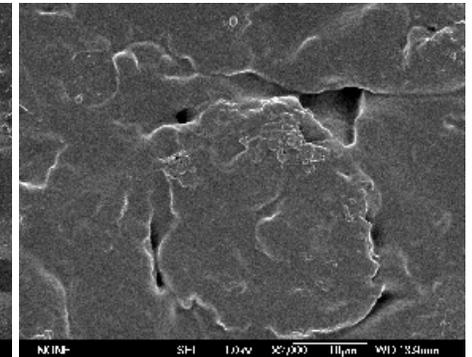
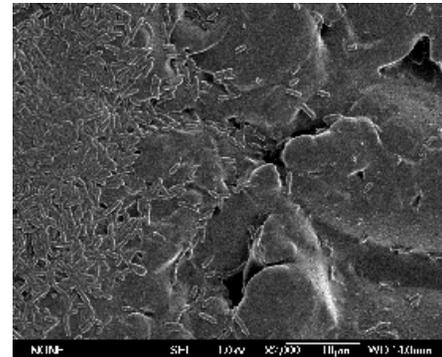


- ◆ Proteases → Proteins
- ◆ Lipases → Lipids (fats and oils)
- ◆ Amylases, glycosidases → Biofilms
- ◆ Lysozyme, Peroxidases → Microbes
- ◆ Organophosphohydrolase → Nerve gas
- ◆ Mixture → Dirt



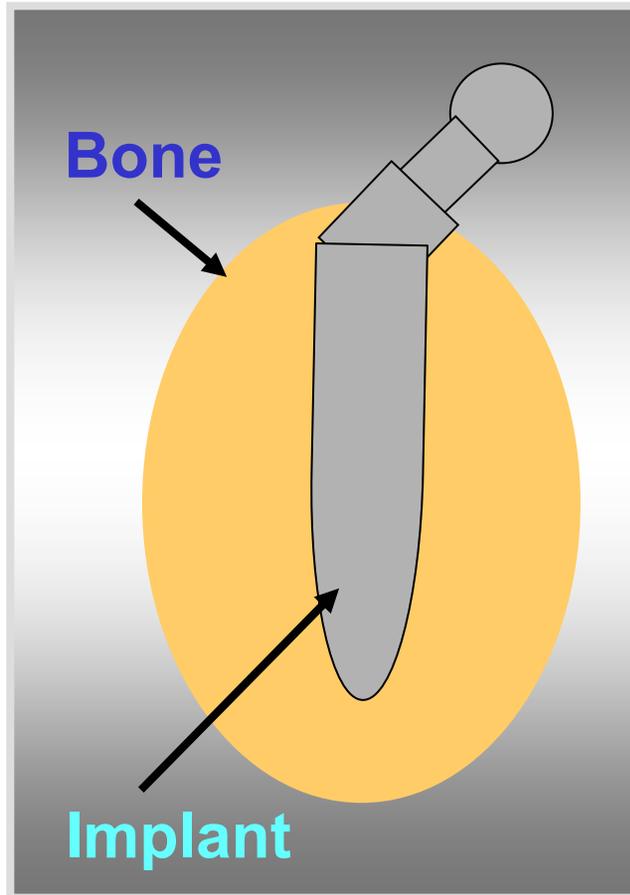
Control

Enzyme



*Pseudomonas aeruginosa* – a common opportunistic pathogen

# Bioengineered nanocomposites for tissue engineering



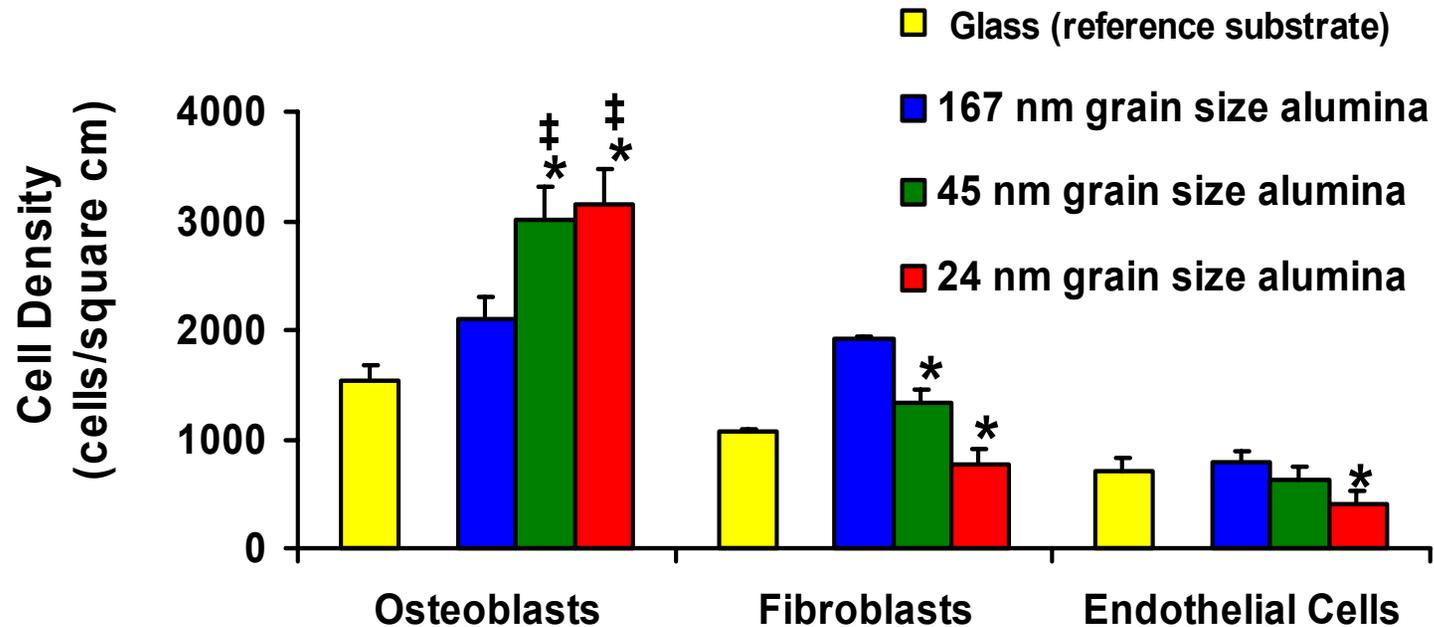
## Implant requirements:

- mechanical behavior close to that of bone
- cellular compatibility
- osseointegration

*Webster, Siegel, Bizios (2000)*

# Cellular compatability

Data for alumina nanoceramic; similar behavior found for other nanoceramics and ceramic/polymer nanocomposites

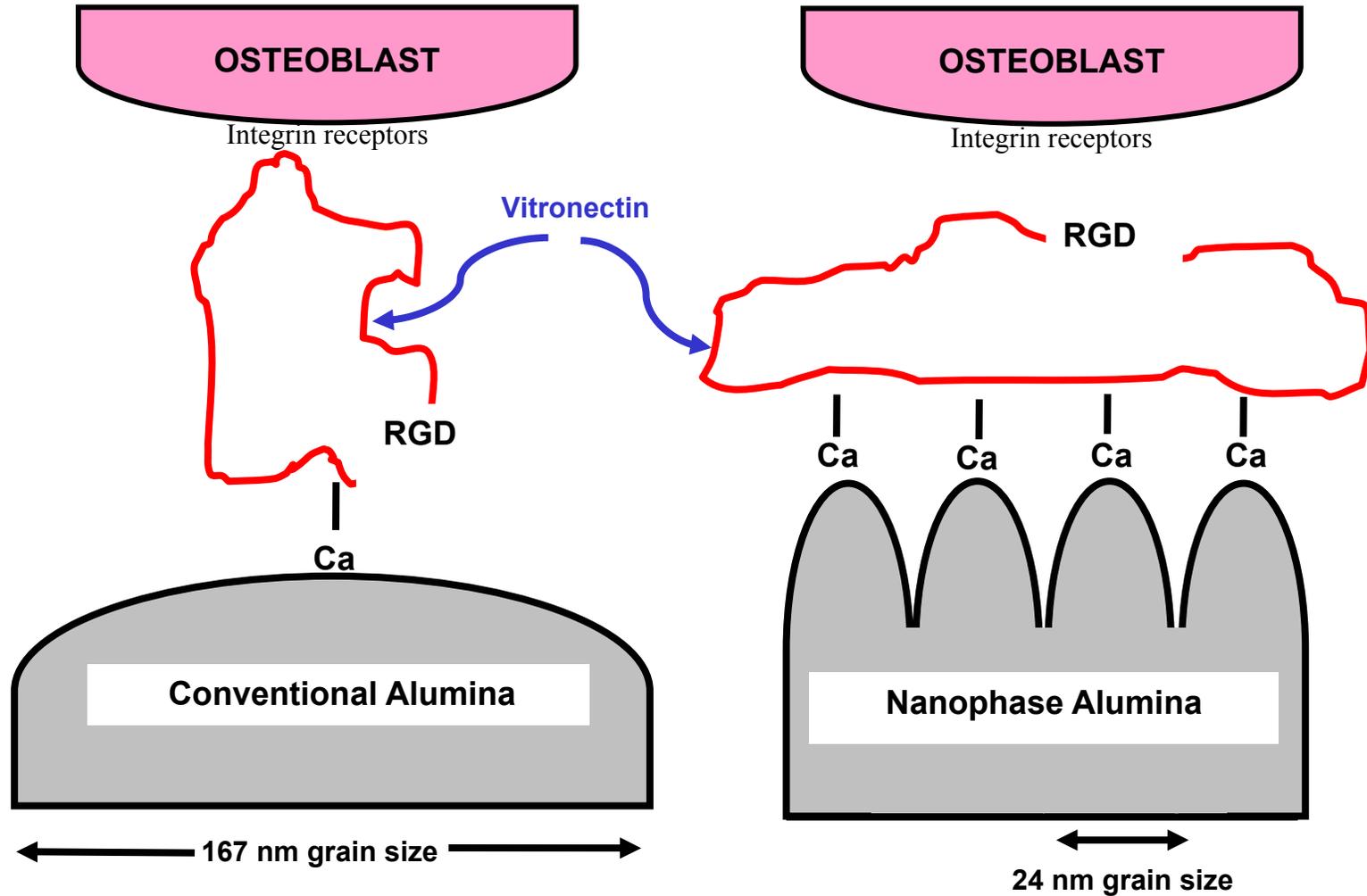


*Webster, Siegel, Bizios (2001)*

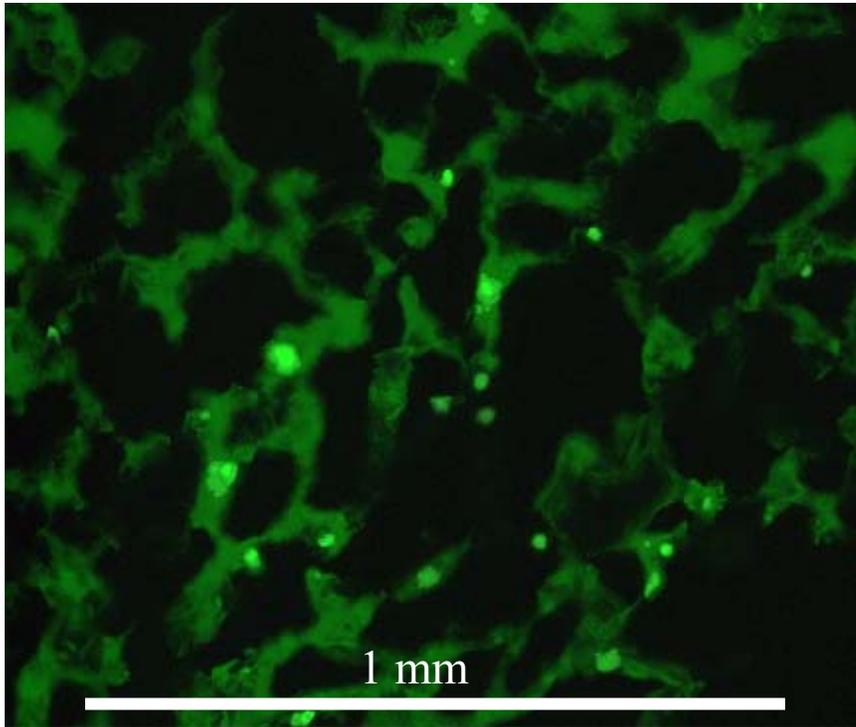


# Osteoblast adhesion

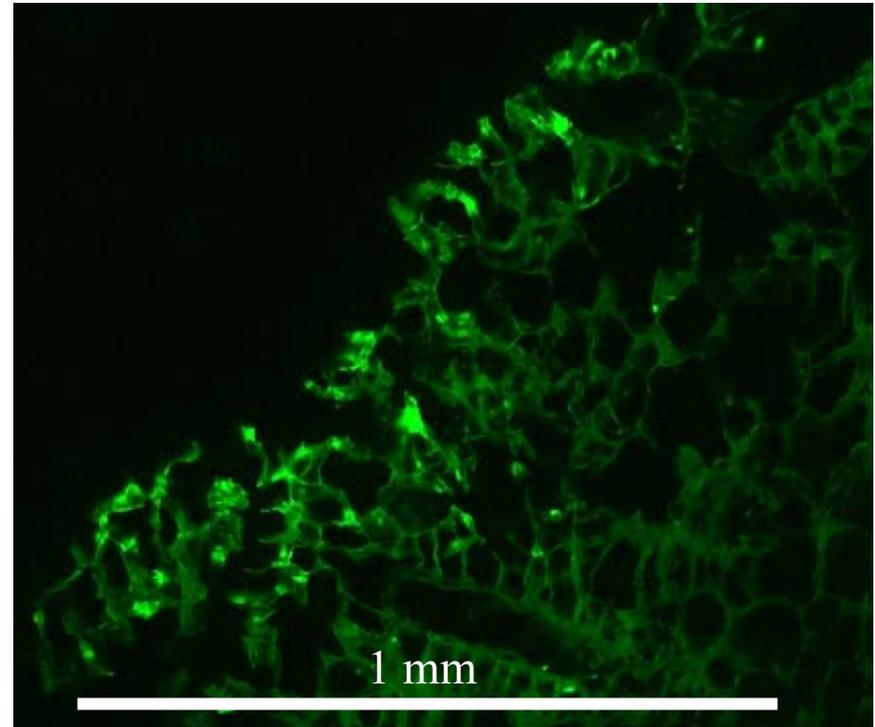
*driven by surface topography*



# Osteoblast distribution in Al<sub>2</sub>O<sub>3</sub>/PLA nanocomposite



**Scaffold Center**



**Scaffold Surface**

Representative fluorescent micrographs illustrating osteoblast distribution 24 hours after cell seeding.

*Dulgar, Bizios, Siegel (2002)*

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# Conclusions:

- **We are now able to create a wide variety of nanoscale building blocks**
- **We are learning how to assemble them into useful nanostructured materials and devices**
- **Society is beginning to benefit from nanoscience and its applications**
- **There is much more to come....!**

