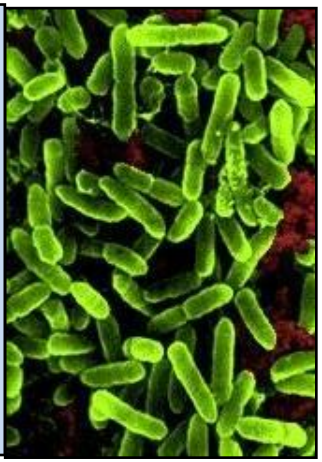
Applications of Nanotechnology to Improve Food and Food Supplies



Jochen Weiss

Food Structure and Functionality Laboratories
Department of Food Science & Biotechnology
University of Hohenheim
Garbenstrasse 25, 70599 Stuttgart, Germany

Future of Food Seminar

Friday 28th 2008, Brussels, Belgium

Nanotechnology & Foods

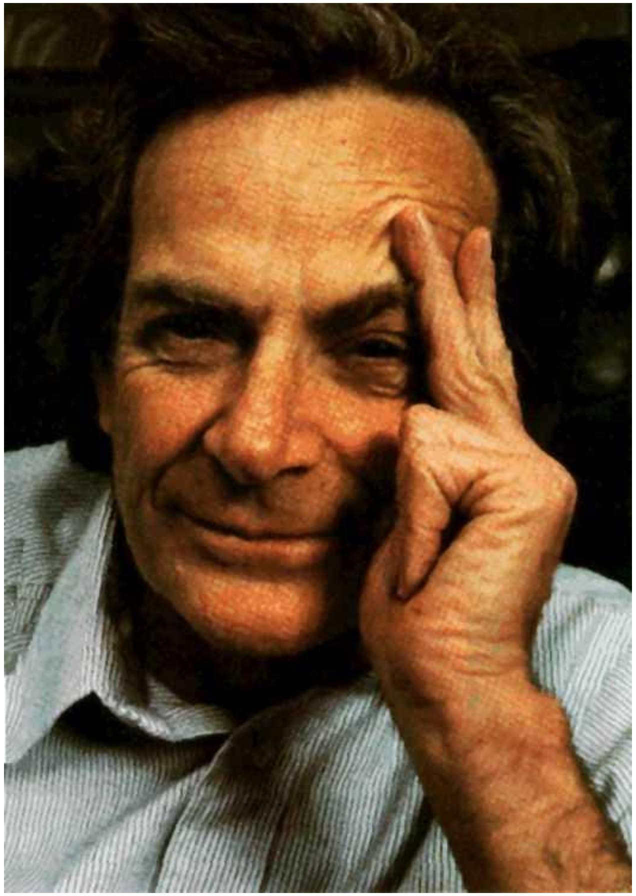
- A Brief Introduction -

What is the all the Fuzz about?

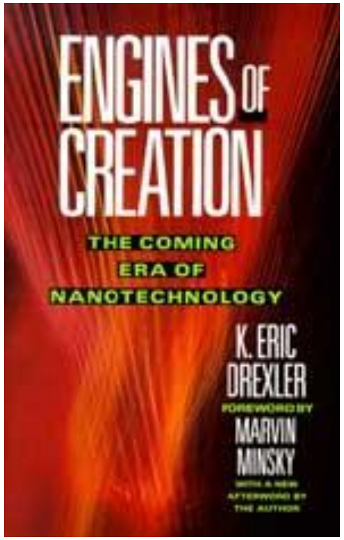
Paradigm Shifts in the Development of Food Systems

The Emergence of Nanotechnology

- Birth with Richard P. Feynman, in his visionary presentation titled “There is Plenty of Room at the Bottom” on December 29th, 1959.
- Became possible with emergence of new analytical tools in the 80’s
  - Scanning tunneling (STM) and field emission scanning microscopy (STM)
  - Atomic force microscopy (ATM)
- Ability to image, measure, model, control and manipulate matter at dimensions of roughly 1 to 100 nanometers
- Properties governed by **quantum mechanics** rather than Newtonian mechanics → surface/interfacial physics and chemistry are of paramount importance



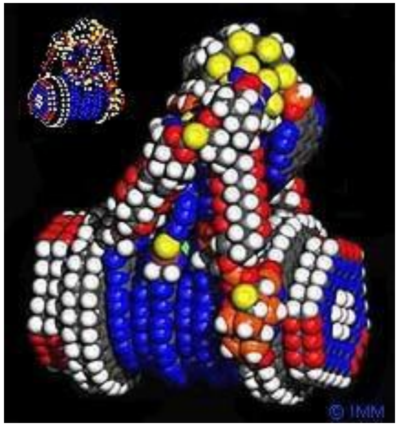
The Original Vision - Molecular Manufacturing

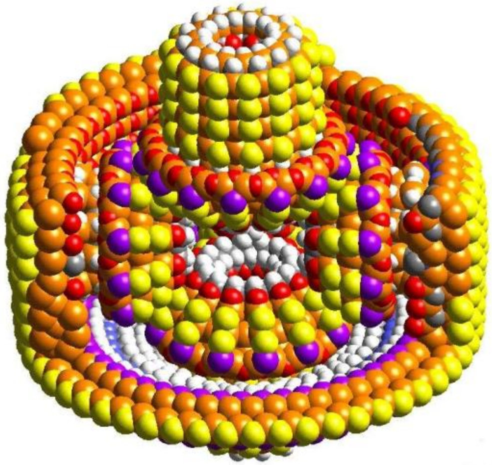


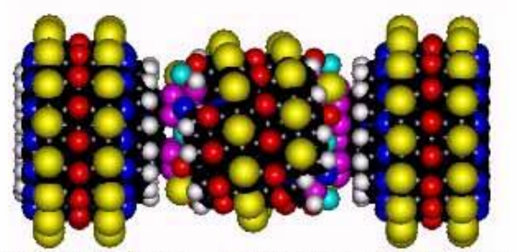
“Engines of Creation: The Coming Era of Nanotechnology”

Book by K. Eric Drexler, 1986

- “Molecular Assemblers“ → Devices capable of precisely positioning atoms and molecules



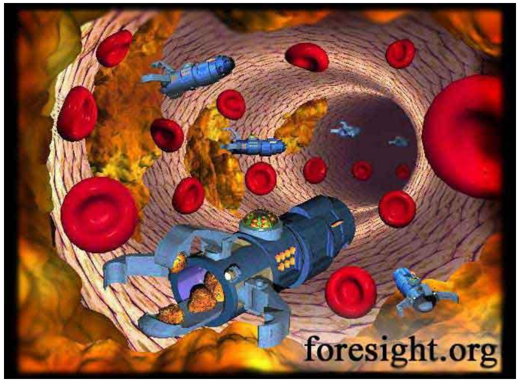




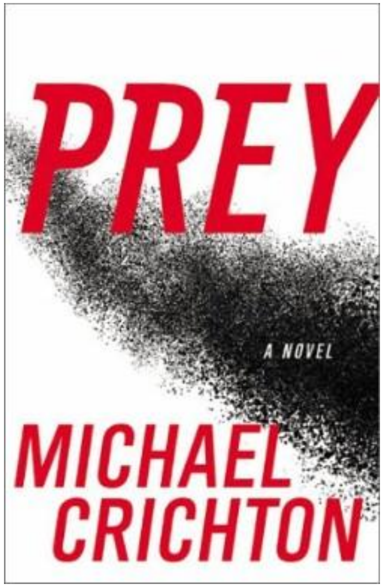
The True Evolution (not Revolution) of Nanotechnology

- Eclectic derivative of established disciplines:
  - Chemistry, Physics, Interface Science, Microfabrication
  - Discoveries are made on established principles and foundations
- Why add "nano"?
  - Allow researchers to highlight that processes or material structures are designed to use specific properties and behaviors at 10^{-7}-10^{-9} m.
- **What it has evolved into (particularly in Food Science and Technology):**
  - **Conceptual and intellectual framework** that enables the design of more complex macroscopic structures using nanometer length-scale building blocks
  - This does represent a paradigm shift from traditional food manufacturing

Fiction Fuels Irrational Concerns

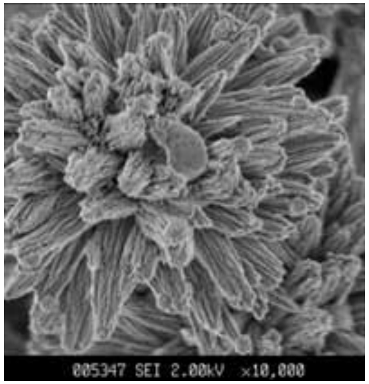


- "Replicating assemblers and thinking machines pose basic threats to people and to life on Earth“ - Drexler
- Speculation about the potential dangers of nanotechnology threatens public support – Smalley



The Reality

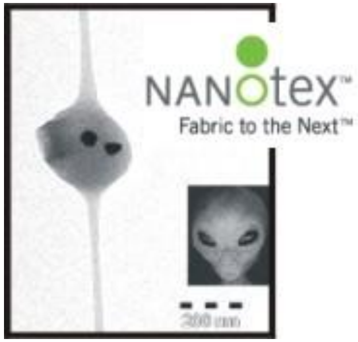
- Everyday Nanotech Products -

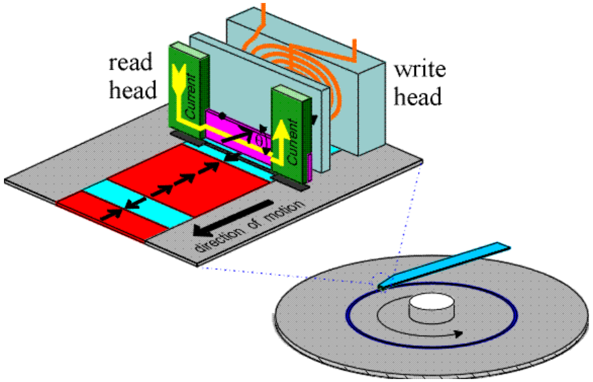


Zeolite catalysts for petrochemical refinery processes

Cosmetics

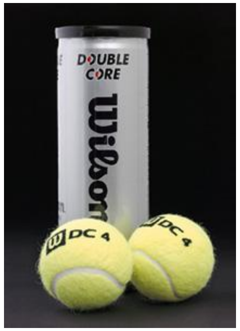
Stain-resistant Textiles

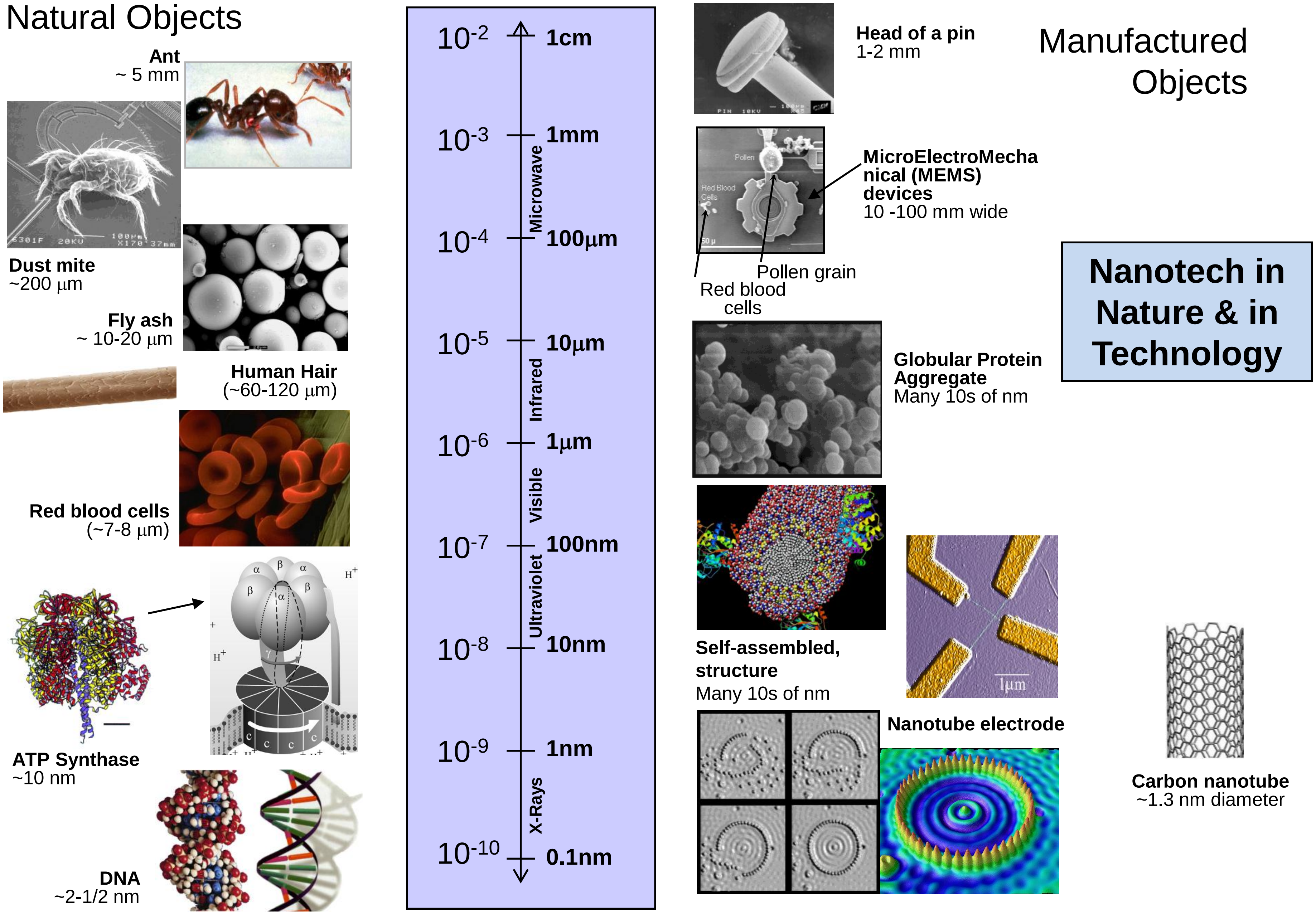




Giant Magnetoresistance for information storage

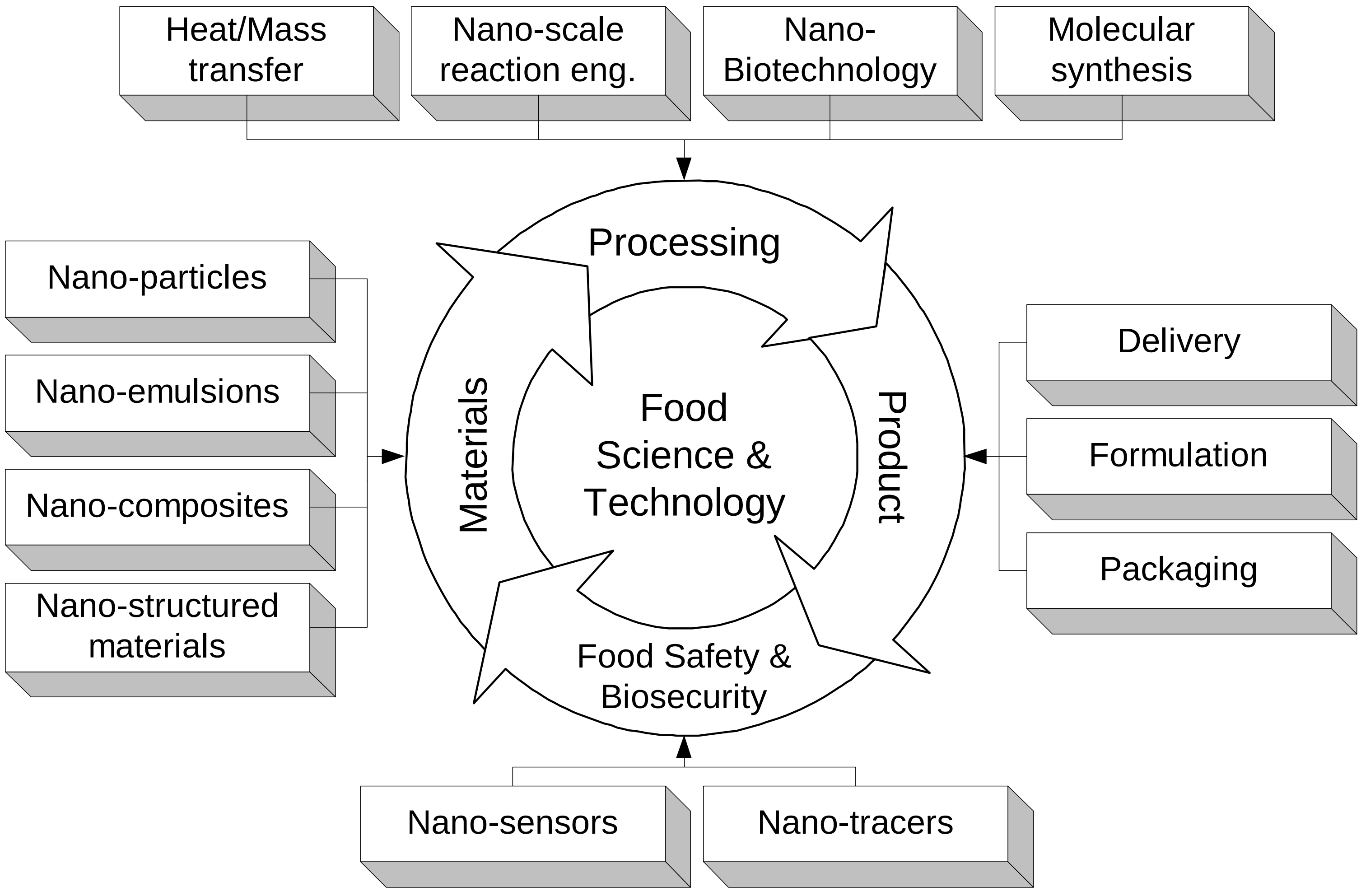
Reinforced tennis racquets and tennis balls





Natural Objects
Ant
~ 5 mm
Dust mite
~200 µm
Fly ash
~ 10-20 µm
Human Hair
(~60-120 µm)
Red blood cells
(~7-8 µm)
ATP Synthase
~10 nm
DNA
~2-1/2 nm
10-2 1cm
10-3 1mm
10-4 100µm
10-5 10µm
10-6 1µm
10-7 100nm
10-8 10nm
10-9 1nm
10-10 0.1nm
Microwave
Infrared
Visible
Ultraviolet
X-Rays
Head of a pin
1-2 mm
Manufactured Objects
MicroElectroMechanical (MEMS) devices
10 -100 mm wide
Pollen
Red Blood Cells
Pollen grain
Red blood cells
Nanotech in Nature & in Technology
Globular Protein Aggregate
Many 10s of nm
Self-assembled, structure
Many 10s of nm
1µm
Nanotube electrode
Carbon nanotube
~1.3 nm diameter

Applications of Nanotechnology In Food Science and Technology



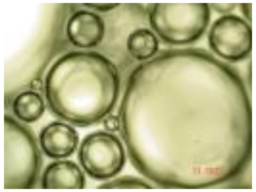
Paradigm Shift: - Fabrication Approaches to Nanoscalar Objects -



Agricultural Raw Materials

Bulk Processing

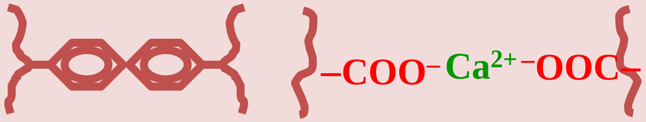
Thermal Treatments
Shearing/Mixing
Homogenization
Extrusion

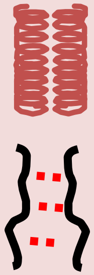


Microstructures

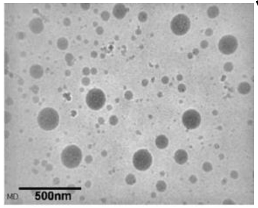
Nanostructures

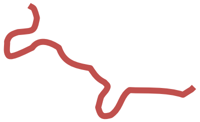
Food Product





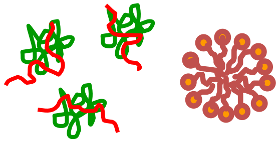
Covalent Bond
Electrostatic Interactions
Salt Bridging
Hydrogen Bonding
Hydrophobic Interactions
VDW Attraction

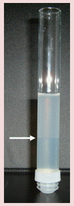


Peptides
Proteins
Oligosaccharides
Polysaccharides

Self Assembly



Phase Transitions
Network Formation
Phase Separation

Food Nanotechnology Applications

Food Safety and Quality

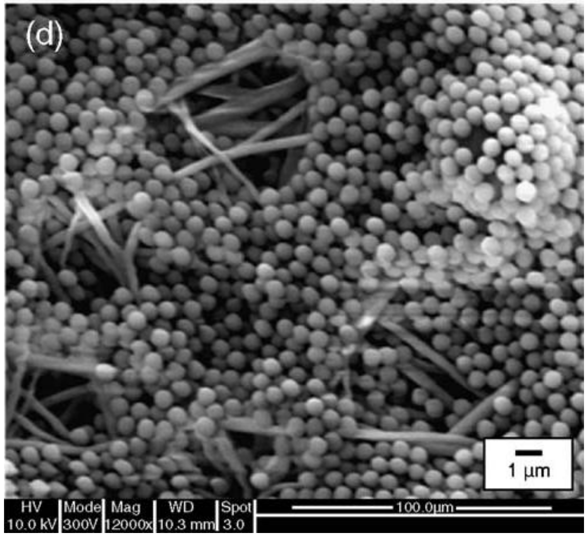
Food Processing

Food Packaging

Ingredient Technologies

I. Use of Nanotechnology in Processing: Nanofiltration

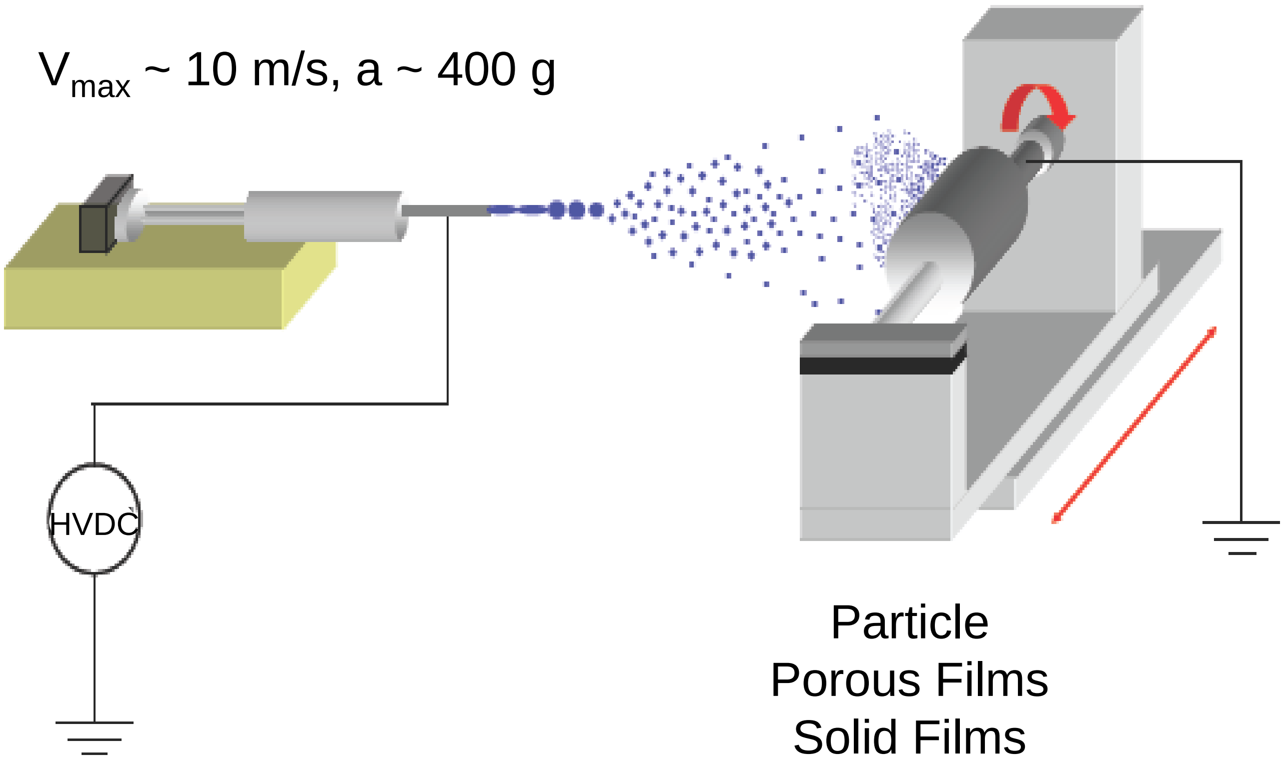
- Based on fabrication of non-woven filter materials
- Individual fiber sizes vary between 10 – 500 nm
- Extremely high surface-volume ratio – excellent for deep filtration or adsorption
- Production via ELECTROSPINNING
- Functionalization of fiber surfaces possible (core-shell spinning, spin-coating,electrostatic deposition)

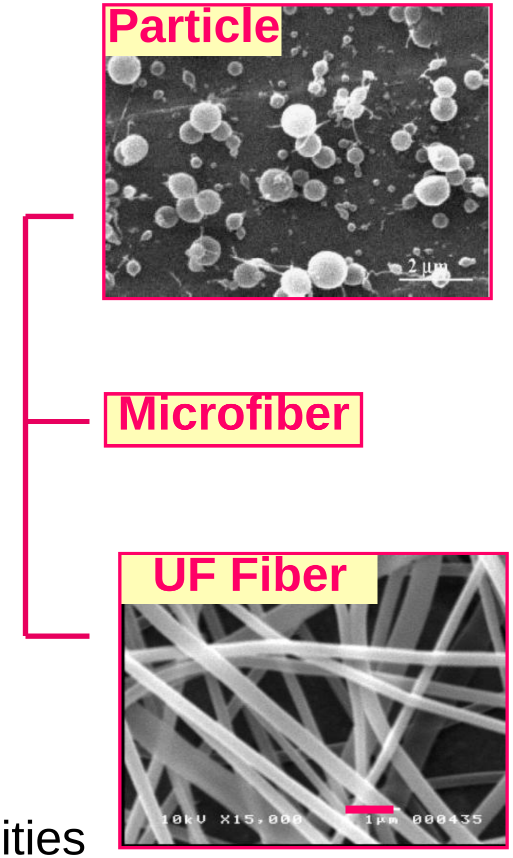


Nanoparticle Filtration

Electrospraying and Electrospinning

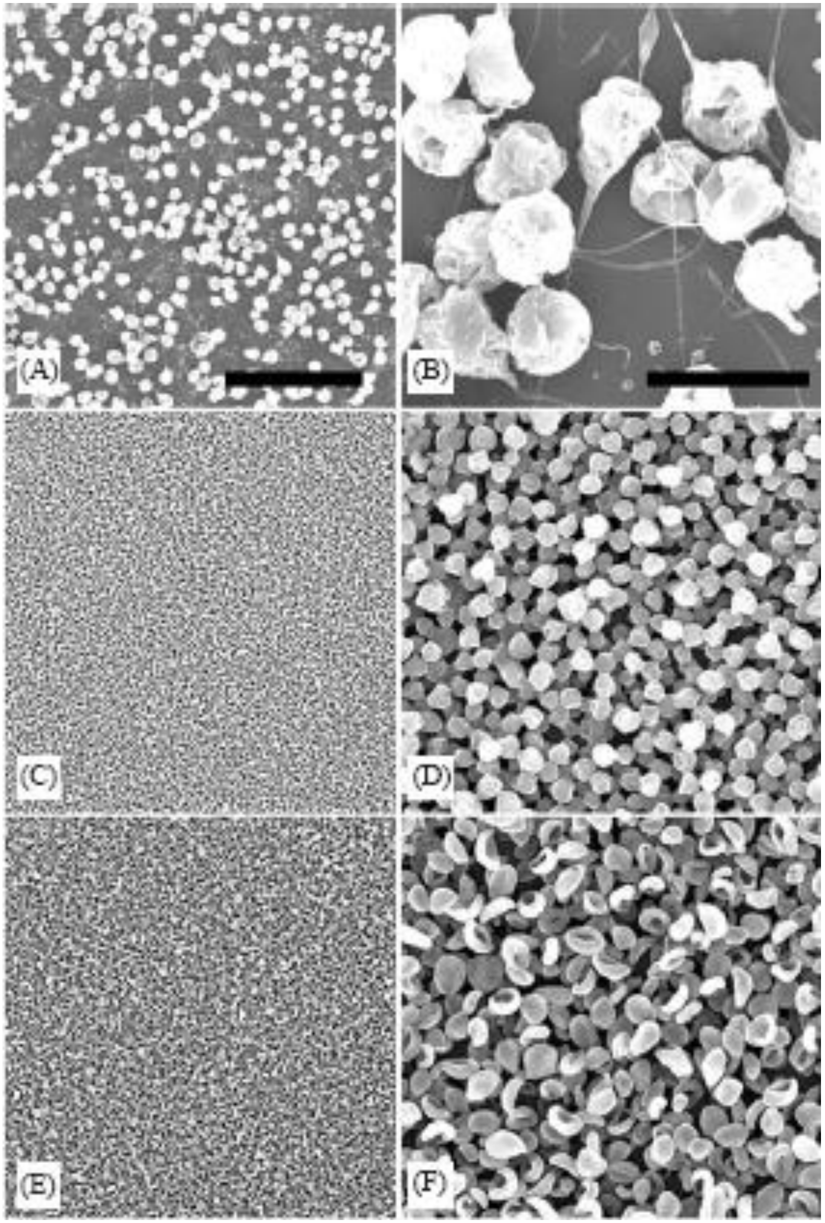
V_{max} ~ 10 m/s, a ~ 400 g





Particle
Porous Films
Solid Films

- The polymer solution is being pumped to the capillary → positively charged polymer solution with high charge densities
- At high applied voltages, the electrostatic repulsions is able to overcome the surface tension, resulting in expulsion of a jet (>10kV)



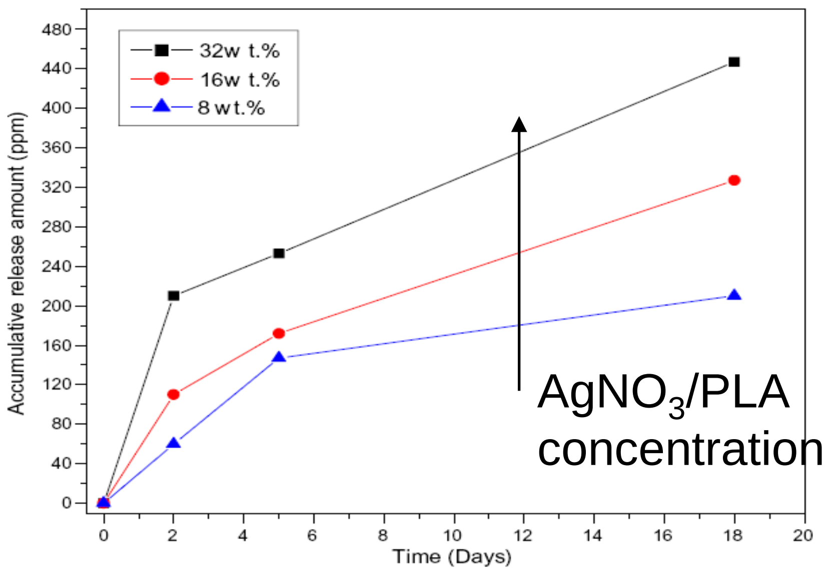
Electrohydrodynamically Sprayed Nanoparticles

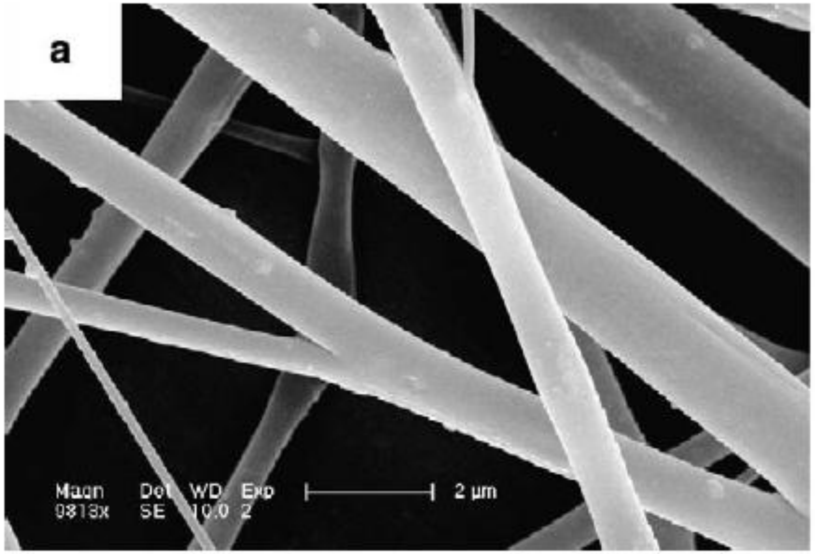
- Uniform particles produced under various conditions
- A & B: Uniform particles ~2.5 um by spraying 5 wt% PLG in acetone (8 kV)
- C & D, PLG in methylene chloride, 15kV
- E & F, PLG in acetonitrile, 10 kV,
- C,D,E,G approx. 80 – 200 nm in size

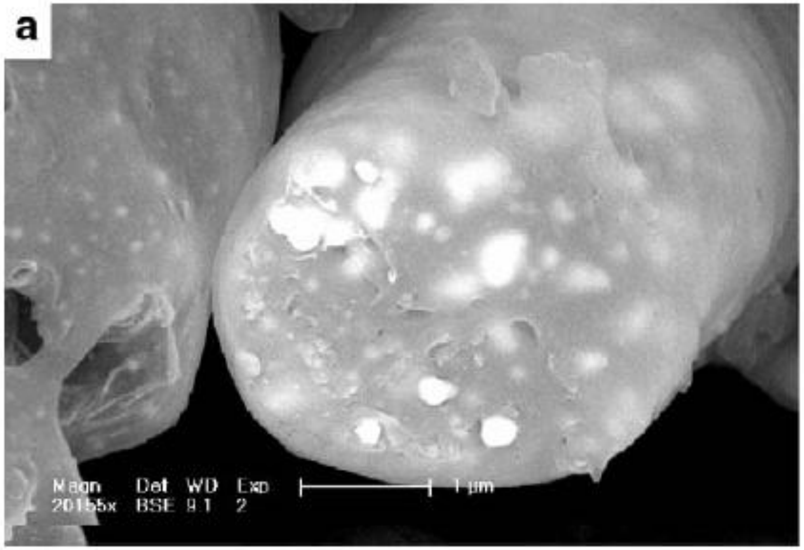
Berkland et al, 2004

Silver Containing Fibers

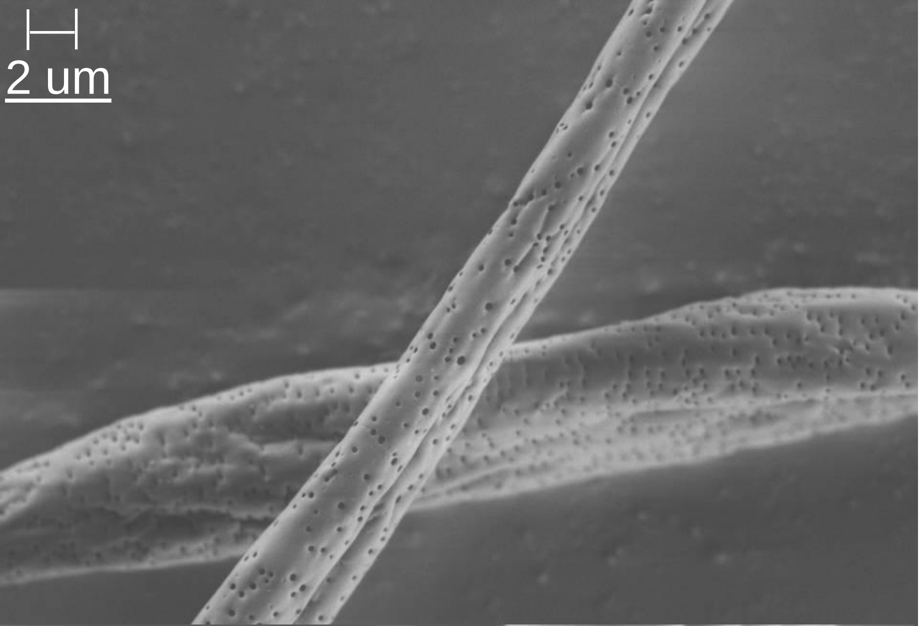
- Biodegradable PLA fibers, containing silver nanoparticles
- High antimicrobial activity due to silver ion release

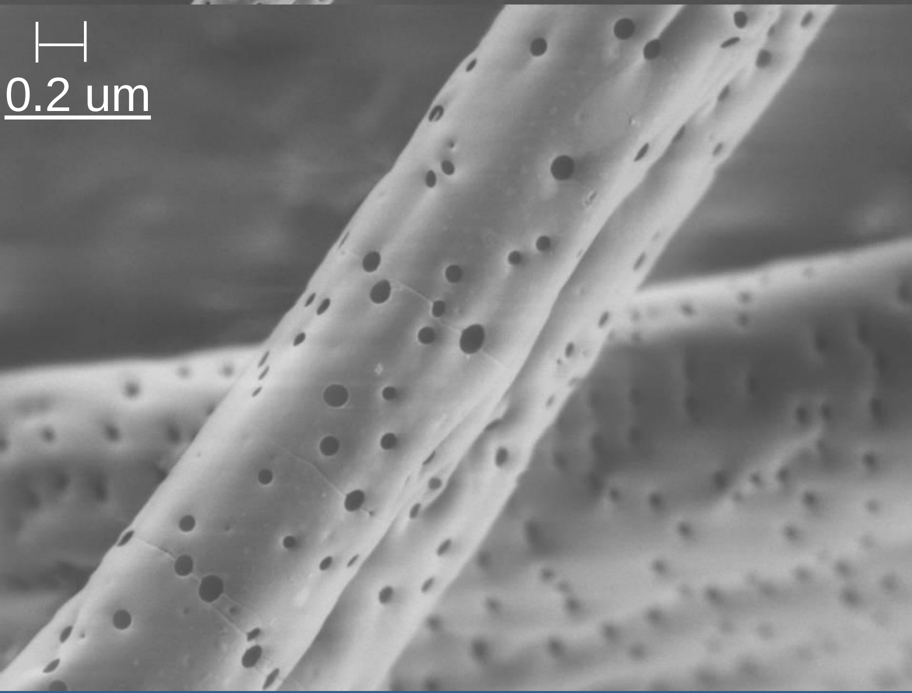






Xu et al, European Polymer Journal, 2006.

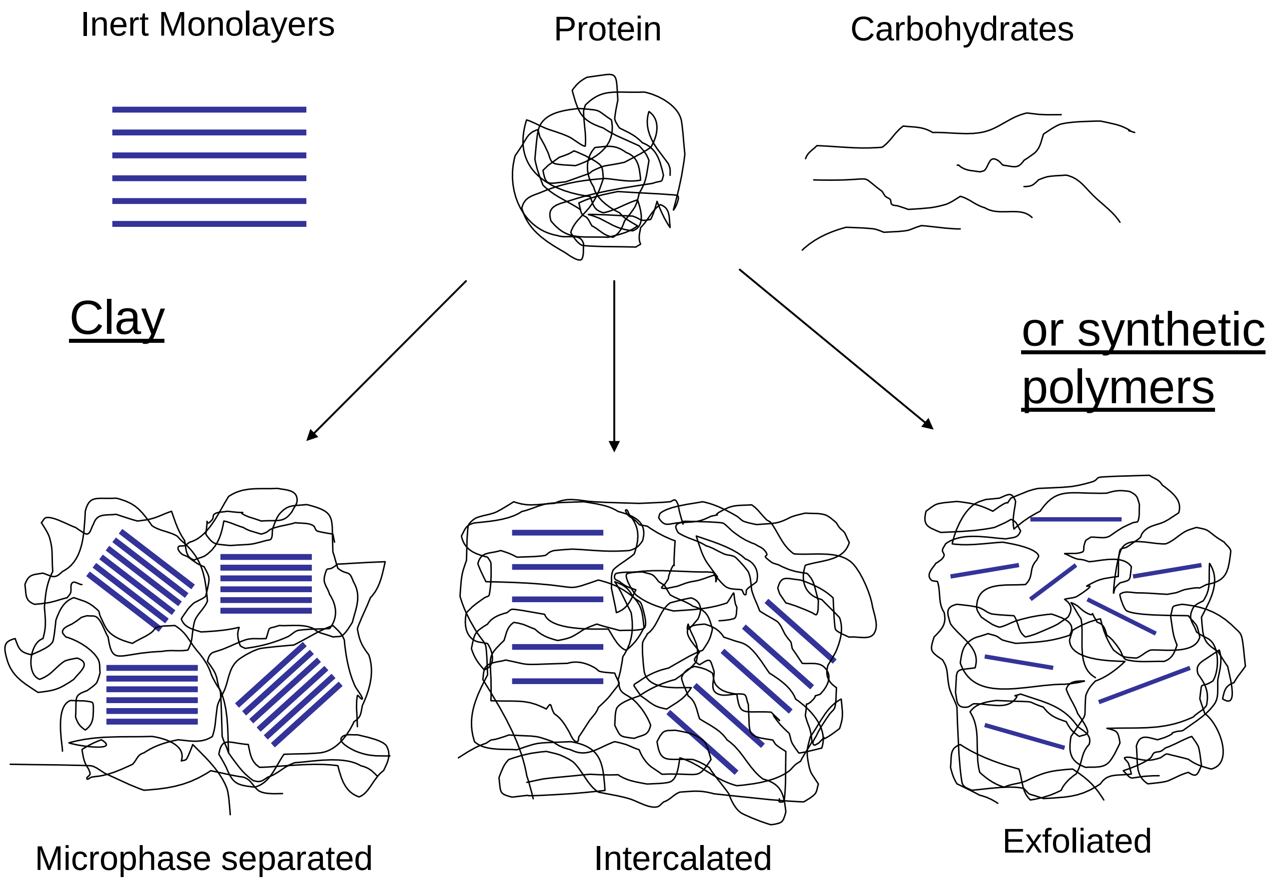




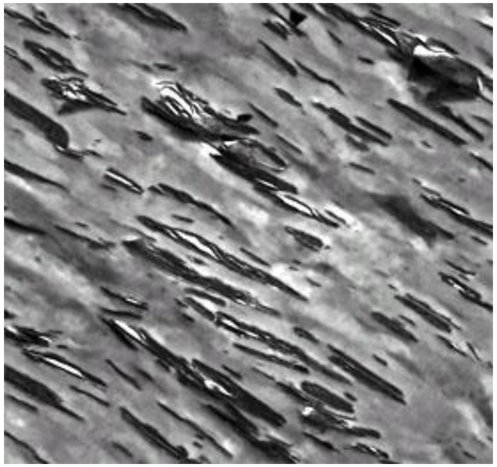
Porous Nanofibers

- Example: Polystyrene (collaboration with University of Tennessee)
- Under appropriate processing conditions, production of porous fibers possible
- Ideal materials for catalysis due to extremely high surface-volume ration and good mass transport
- Enzyme Immobilization

II. Use of Nanostructures in Packaging: Nanoclay Composites



- Torturous
- Path
- Reduced O_2 and H_2O transmission
- Microwavable
- Increased mechanical strength

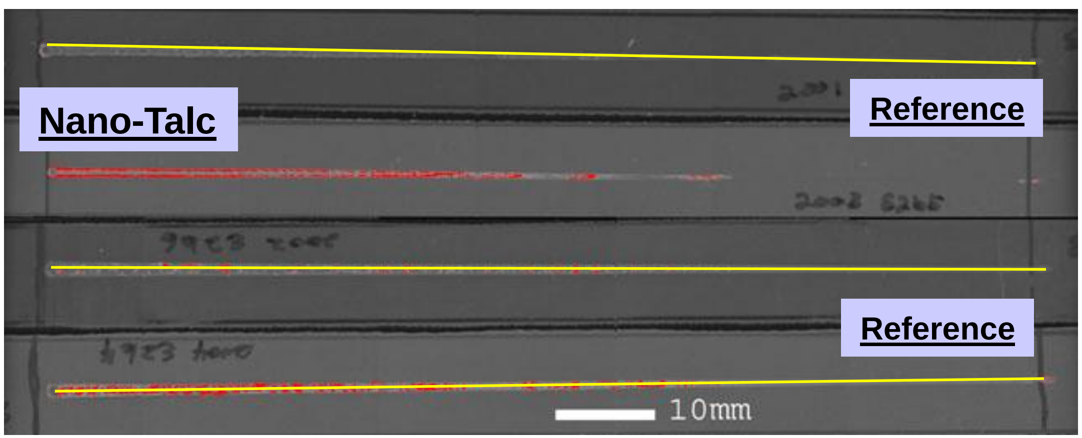


Performance of Exfoliated Nanocomposite Packages

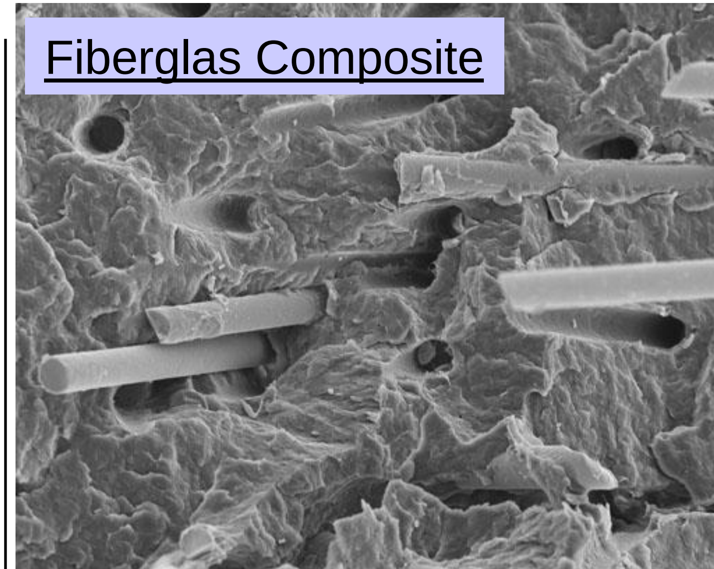
- Increased resistance to scratch and tear
- Increased resistance to high-temperature exposure – materials can be retorted
- *Difficulty:* chemical bonding of clay/particles to polymer matrix

Scratch Test - Linear Load Increase at 100 mm/s

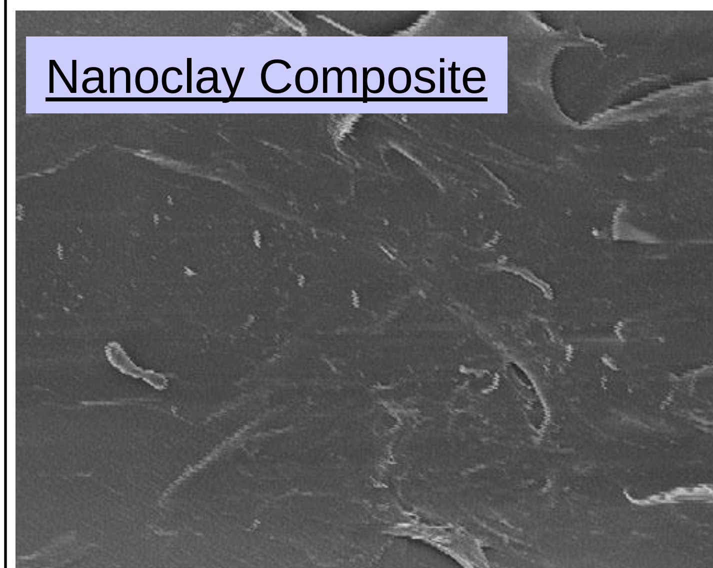
50N ← **5N**



Scratch Direction ←



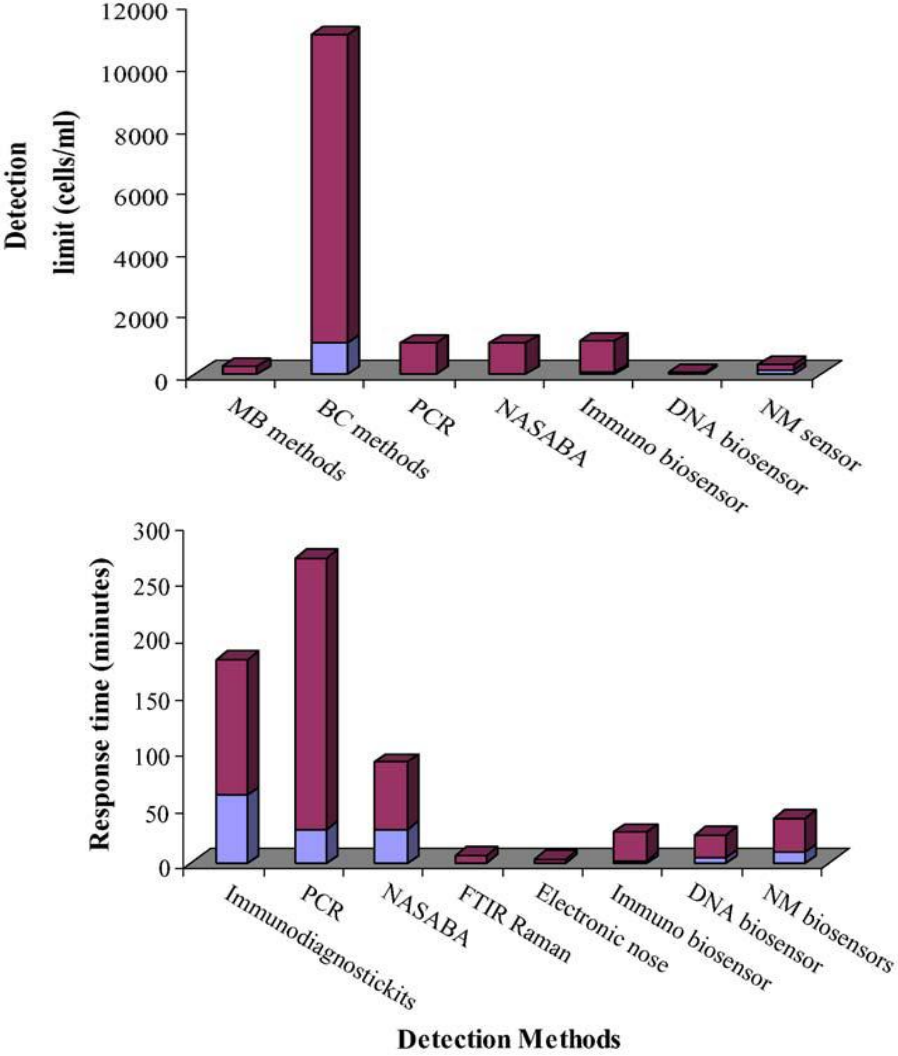
Surface after extensive stress testing



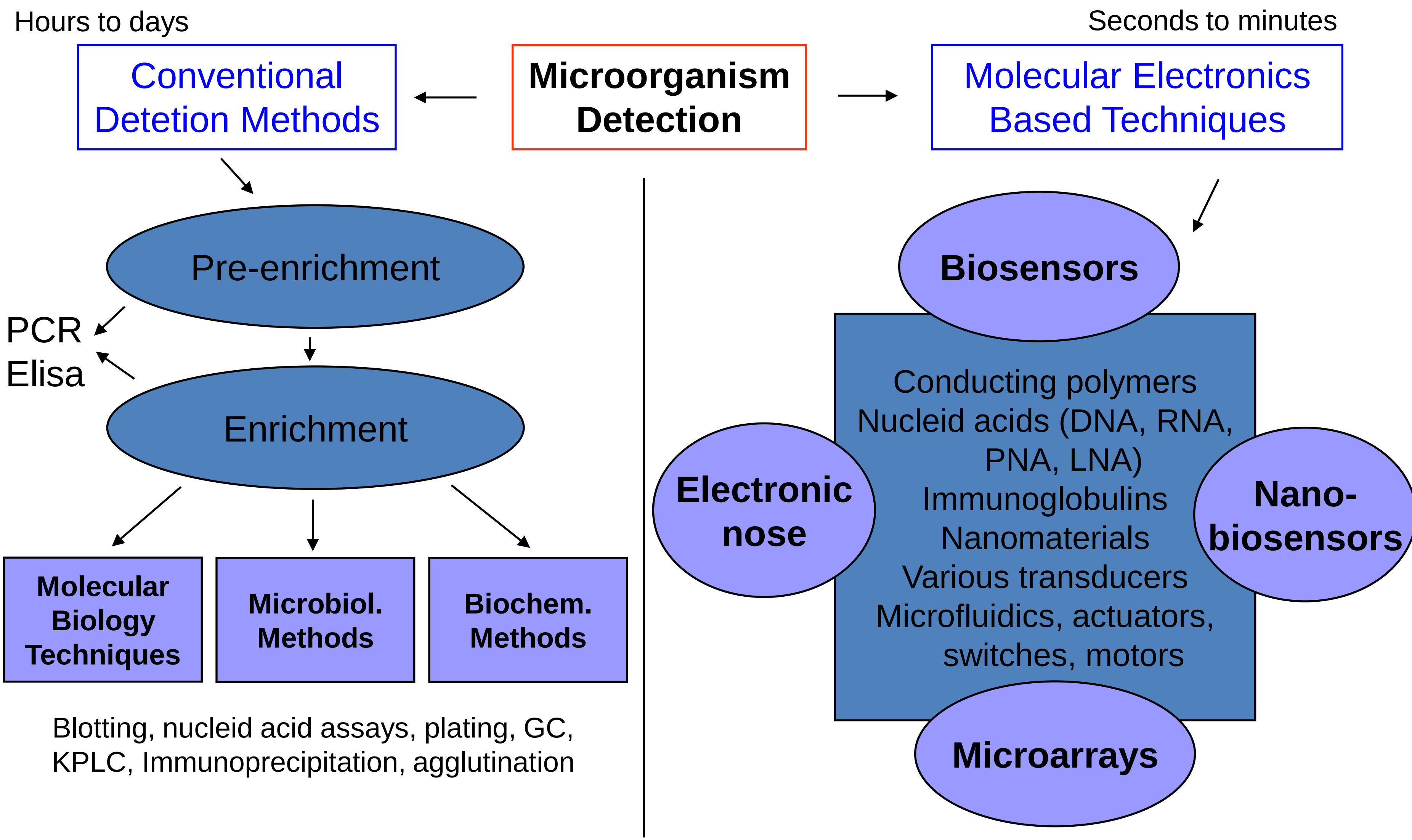
Courtesy Texas A&M, Mat. Science

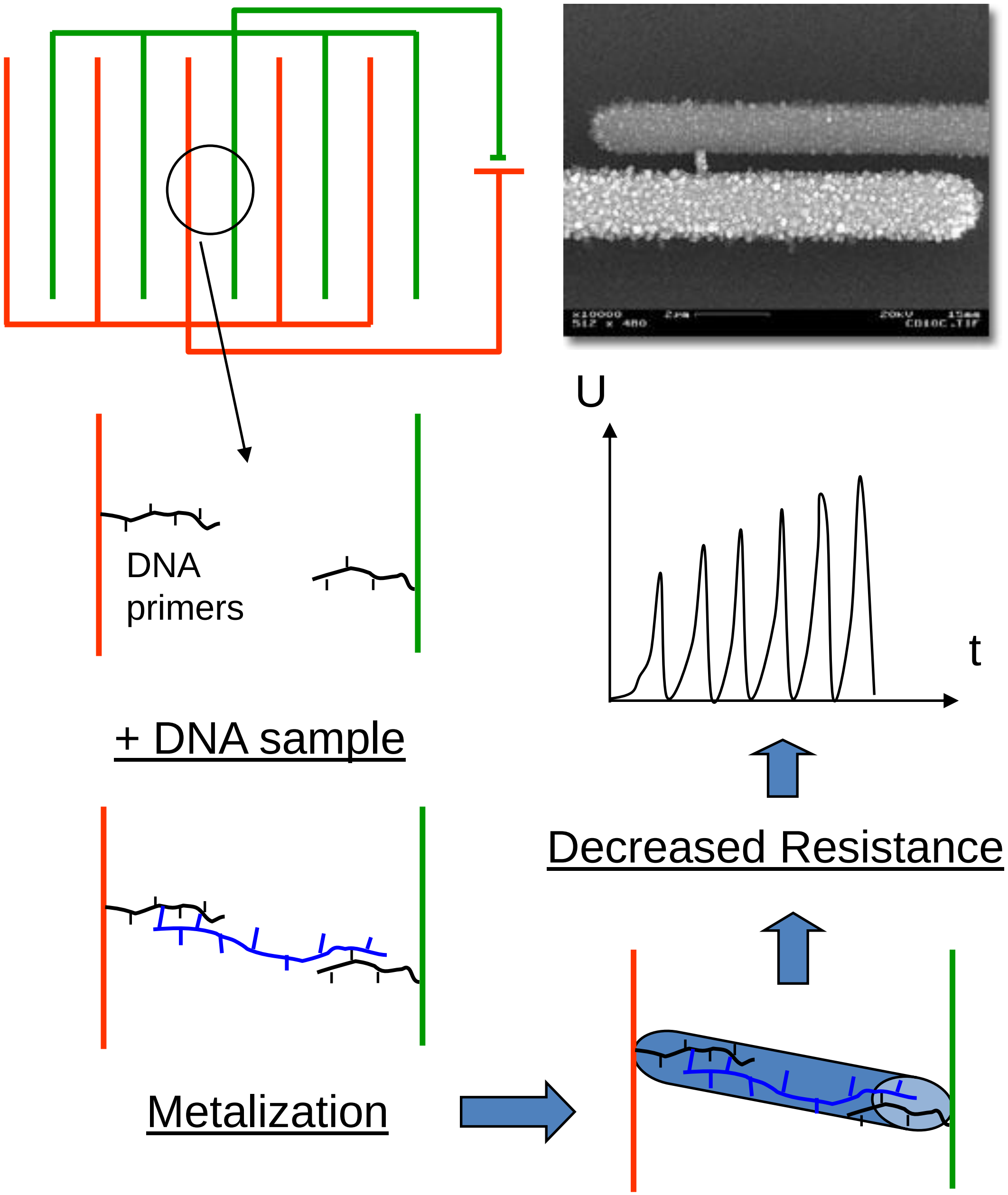
III. Use of Nanotech in Food Safety: Biomolecular Sensors for Food Pathogens

- Application of new materials:
  - Carbon, Au, Zn
  - Quantum Dots
  - Nanocomposites
  - Conducting polymers
  - Langmuir-Blodget films
  - Self-assembled monolayers
  - Microfluidics
  - Molecular switches and gates
- Advantages:
  - Smaller size
  - Quicker response time (seconds to minutes)
  - Reusability
  - Portability
  - Multi-analyte detection
  - High sensitivity → 10 cells/0.1ml, 10^{-2} cfu/ml, 10^{-14}M oligos



Pathogen Sensor Overview



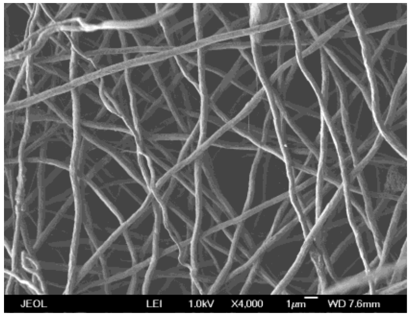


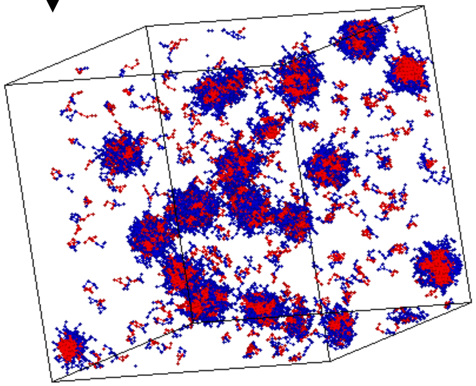
Example: Single DNA Detection

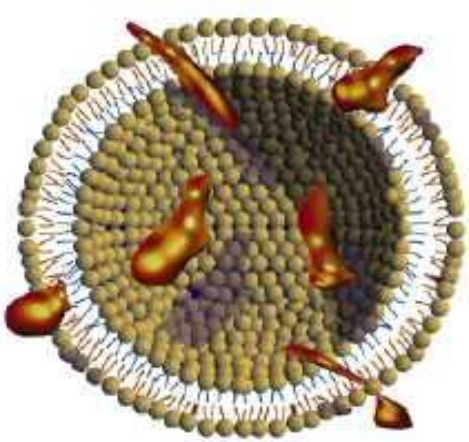
- Simple Test Kit Based on single DNA binding to primers
- DNA us coated with a conducting metal
- Resistance greatly decreases as bound & coated DNA can transmit electrons
- With increasing amperage, connection is severed → individual event
- Allows counting of DNA

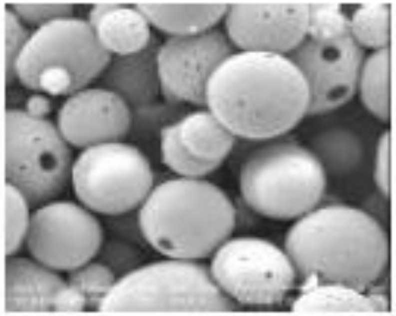
IV. Functional Ingredients From Nanostructures

- Microemulsions
- Liposomes
- Nanoemulsions
- Particles
- Fibers

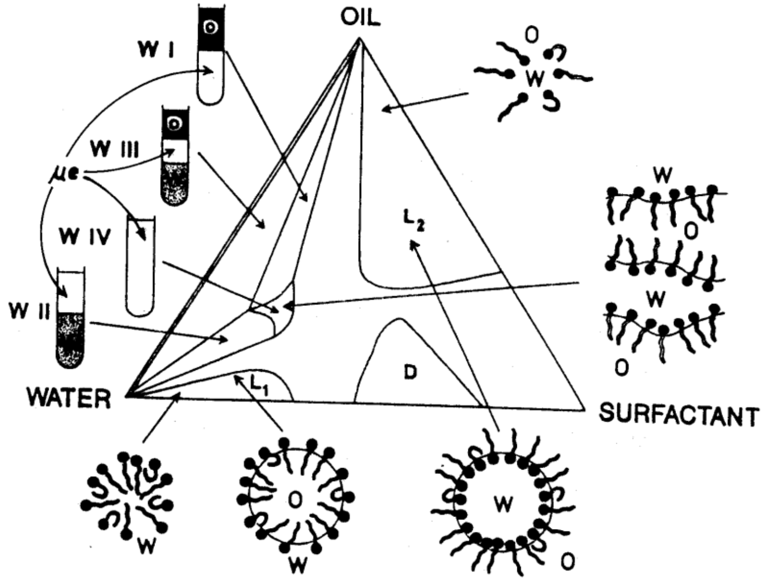


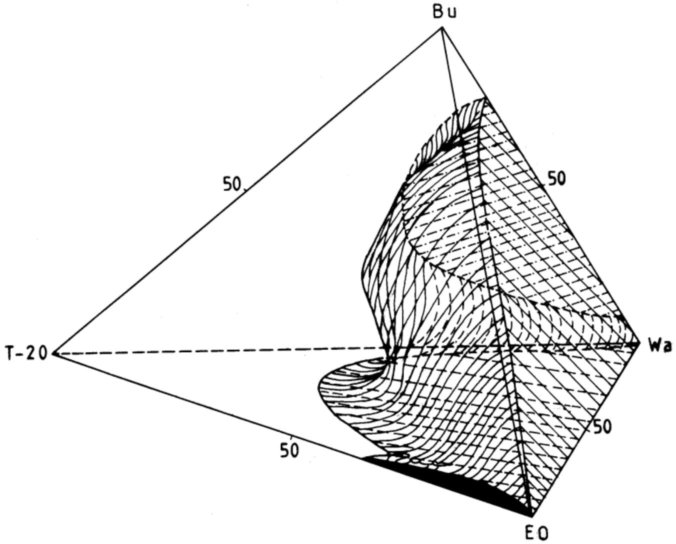






A. Microemulsions



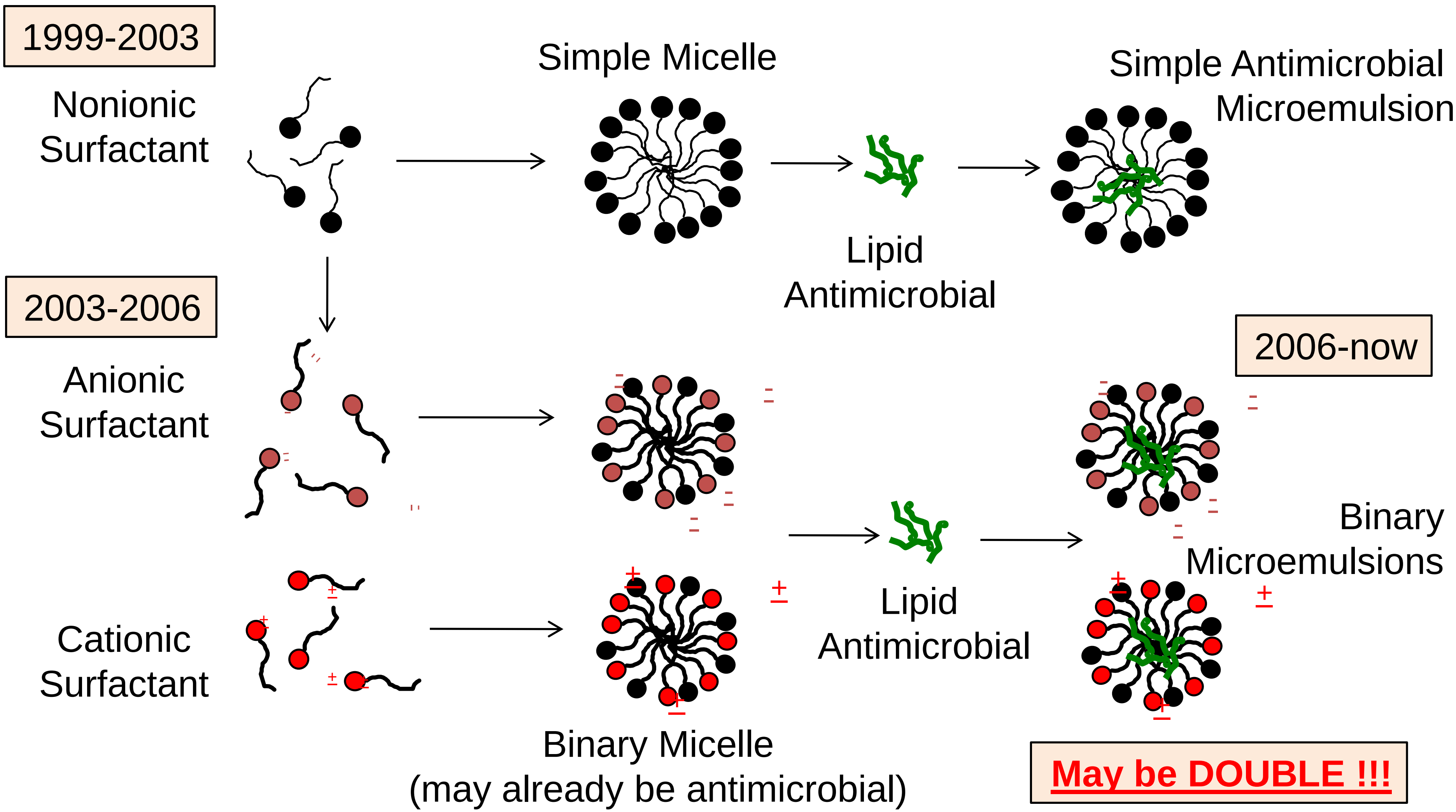


Example of a ternary phase diagram of water-oil-surfactant mixtures

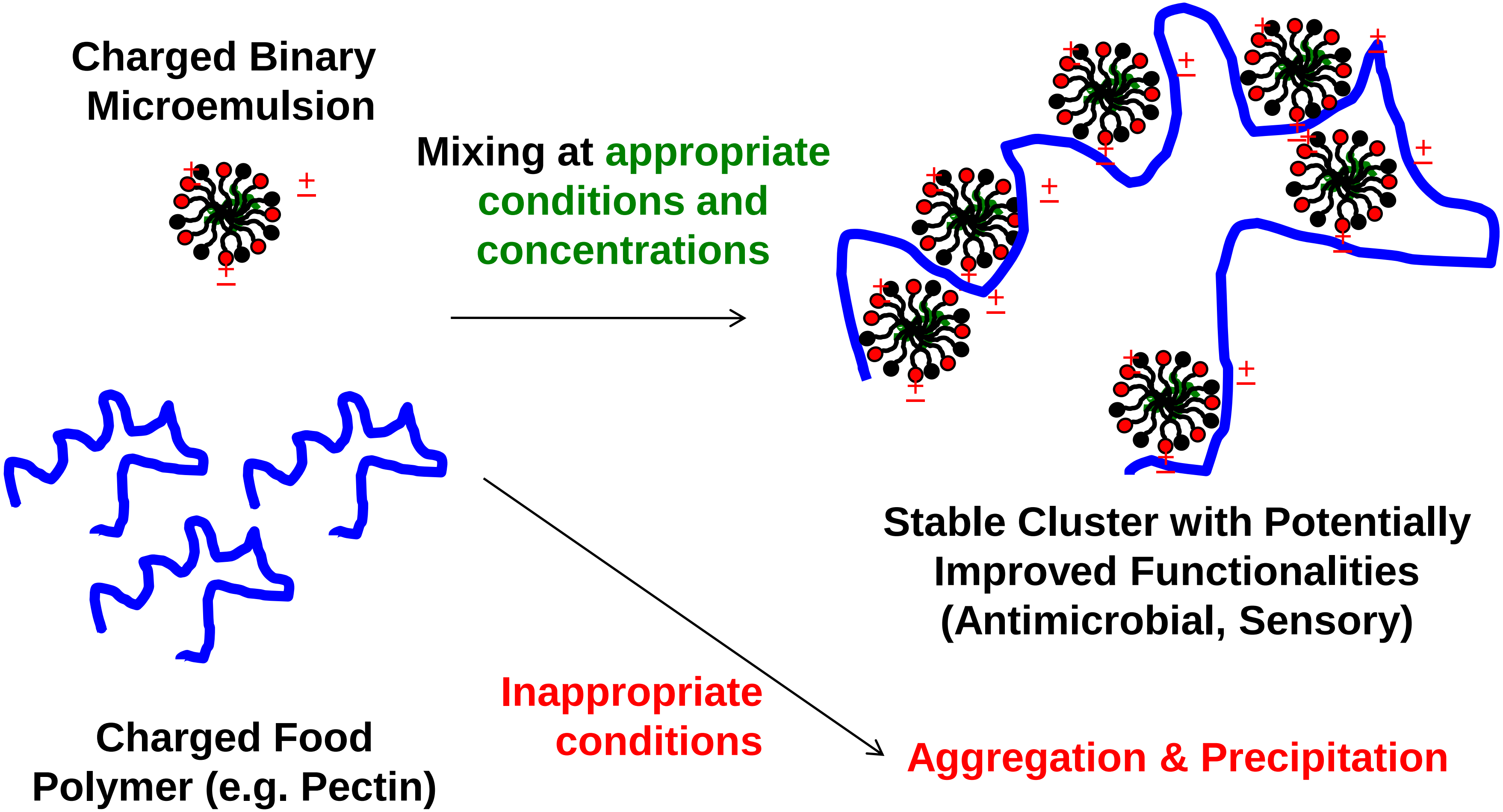
Current Science, 2001, Vol. 80, pp.990-1002

- Microemulsions are ‘thermodynamically stable’. In contrast to emulsions.
- They are isotropic solutions that are typically transparent
- Like emulsions, their stability can be influenced by addition of salt, other additives, temperature or pressure.
- Microemulsions can be prepared from milky emulsions by addition of short chain alkanols or by addition of oil to a mixed surfactant system.
- As such they are three or four component systems
  - Water/amphiphile/oil
  - Water/surfactant/co-surfactant/oil

Development of Microemulsions

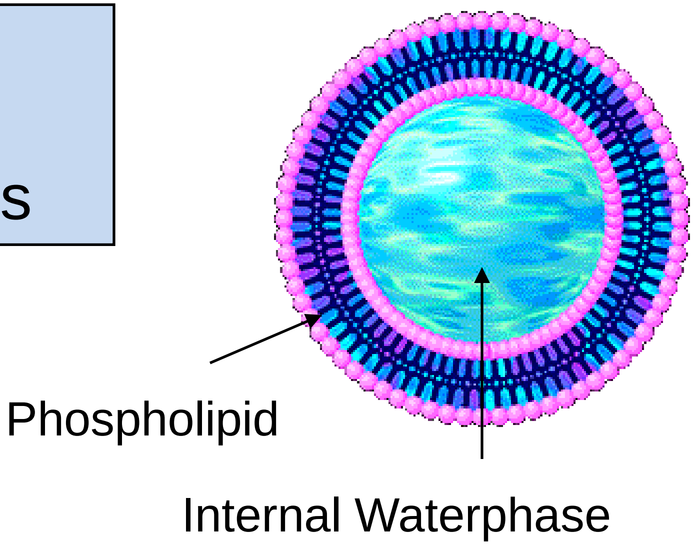


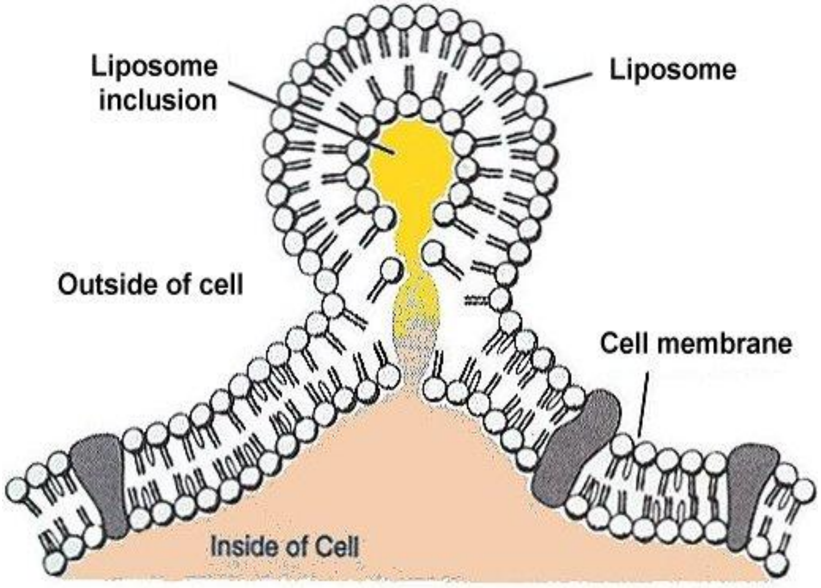
On the Horizon: Formation of Microemulsion – Polymer Clusters



B. Liposomes:
Using Polar Lipids as Building Blocks

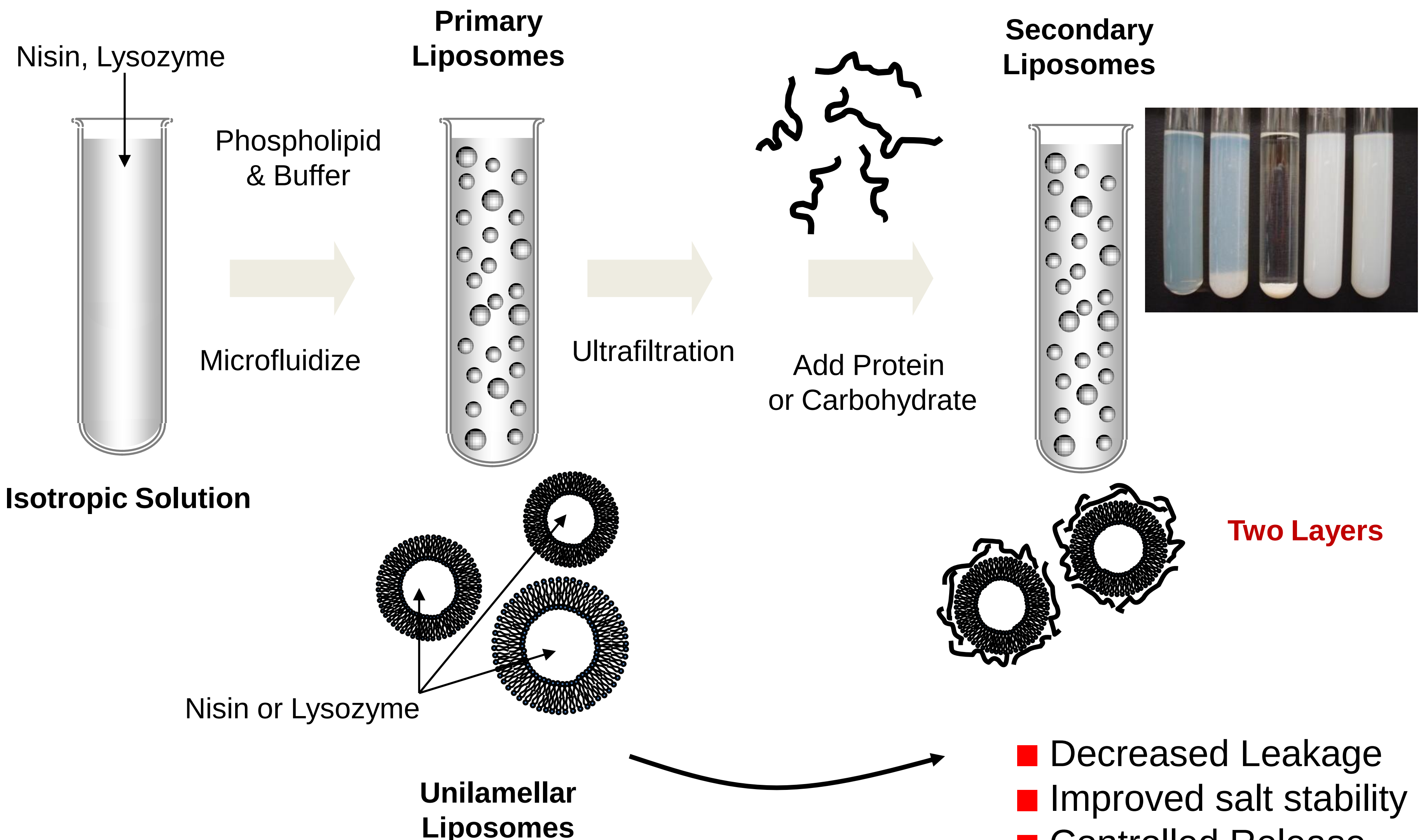
- Spherical membrane structure (bilayer)
- Base materials (phospholipids) widely available in nature
- Materials digestible
- Good interactions with cell membranes
- Internal pH und electrolyte concentrations adjustable
- Suitable for both lipophilic and hydrophilic compounds





Acceptance of liposome into cell

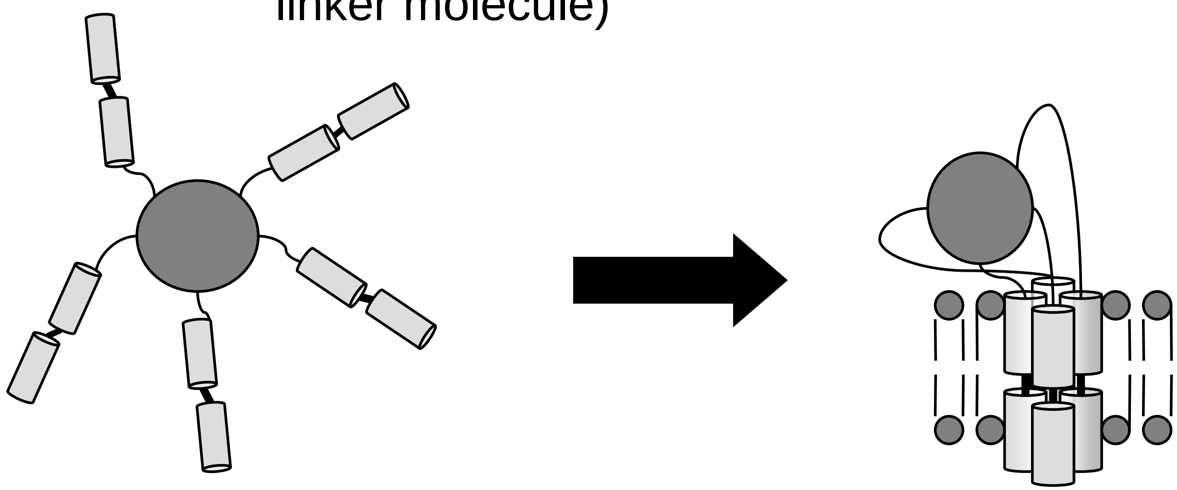
Double-Layered Liposomes



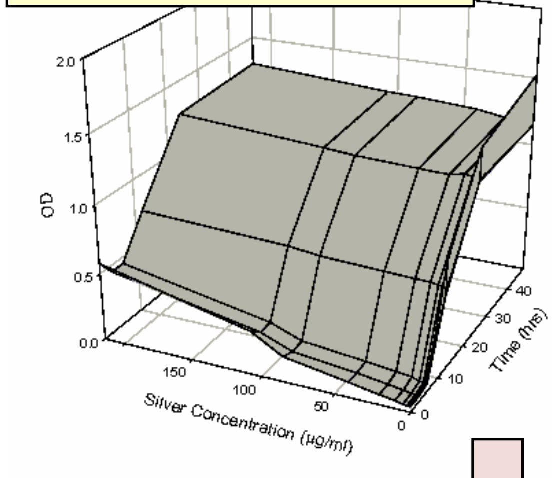
- Decreased Leakage
- Improved salt stability
- Controlled Release

C. Biopolymeric Nanoparticles as Ingredients

- Biopolymer Nanoparticles
  - Solid Particles with diameters < 100 nm
  - Basis of modern anti-cancer drug delivery systems
  - Extremely high bioactivity
  - Als carrier of antimicrobial components:
    - As part of the particle matrix structure
    - Adsorbed at the surface (direct oder via linker molecule)

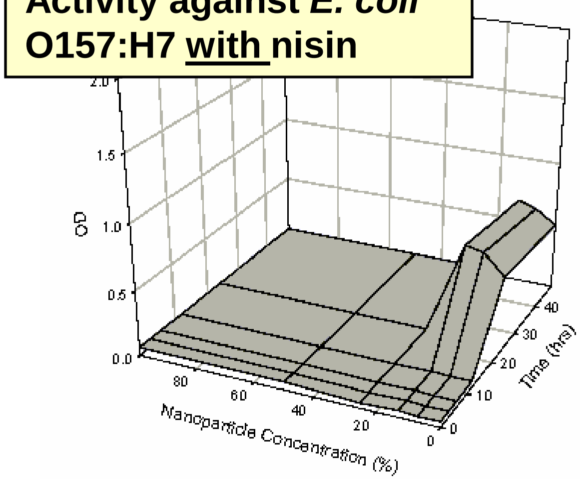


Activity against *E. coli* O157:H7 without nisin

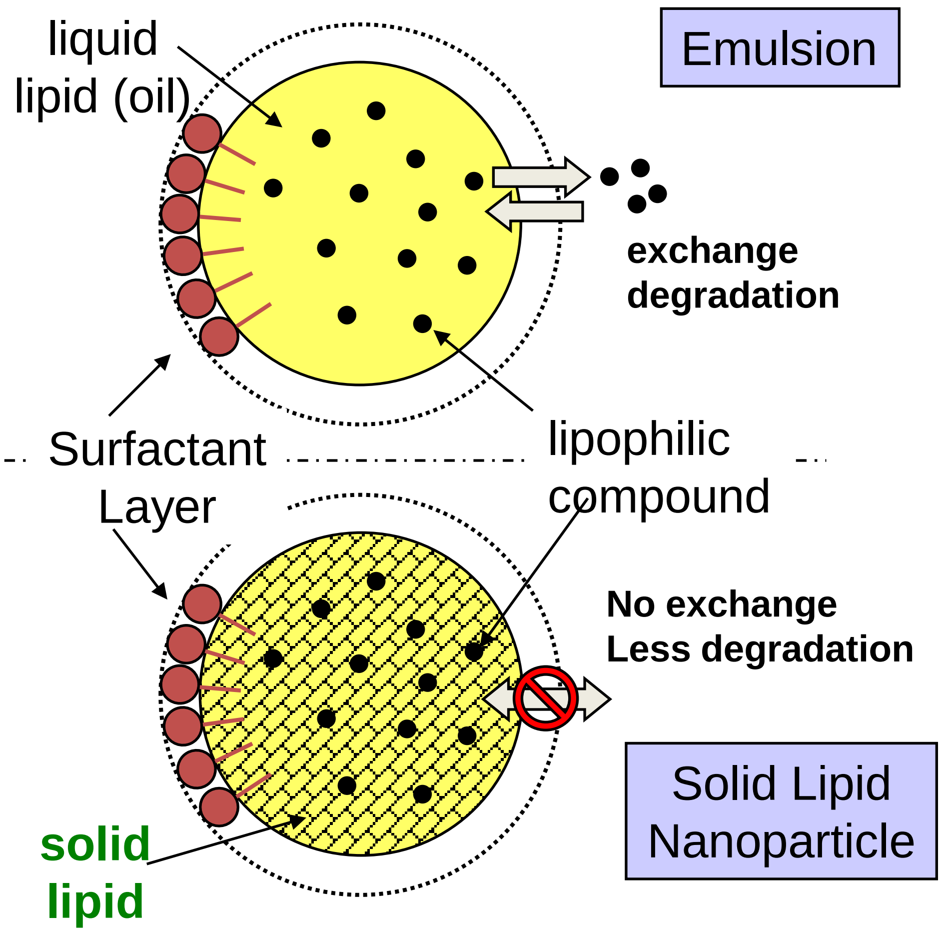


Addition of nisin

Activity against *E. coli* O157:H7 with nisin

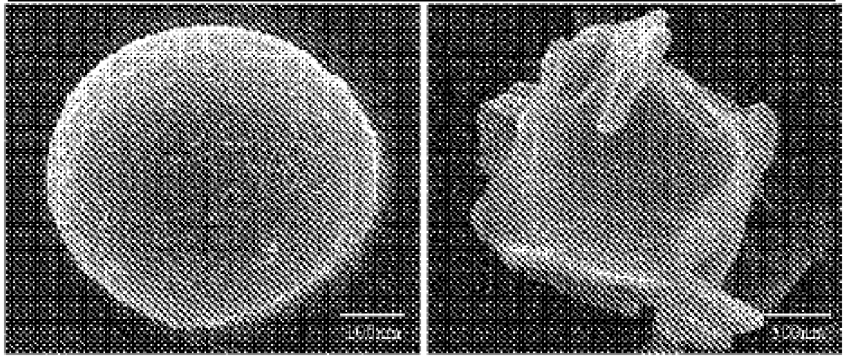


D. “Solid Lipid Nanoparticles” (SLN)



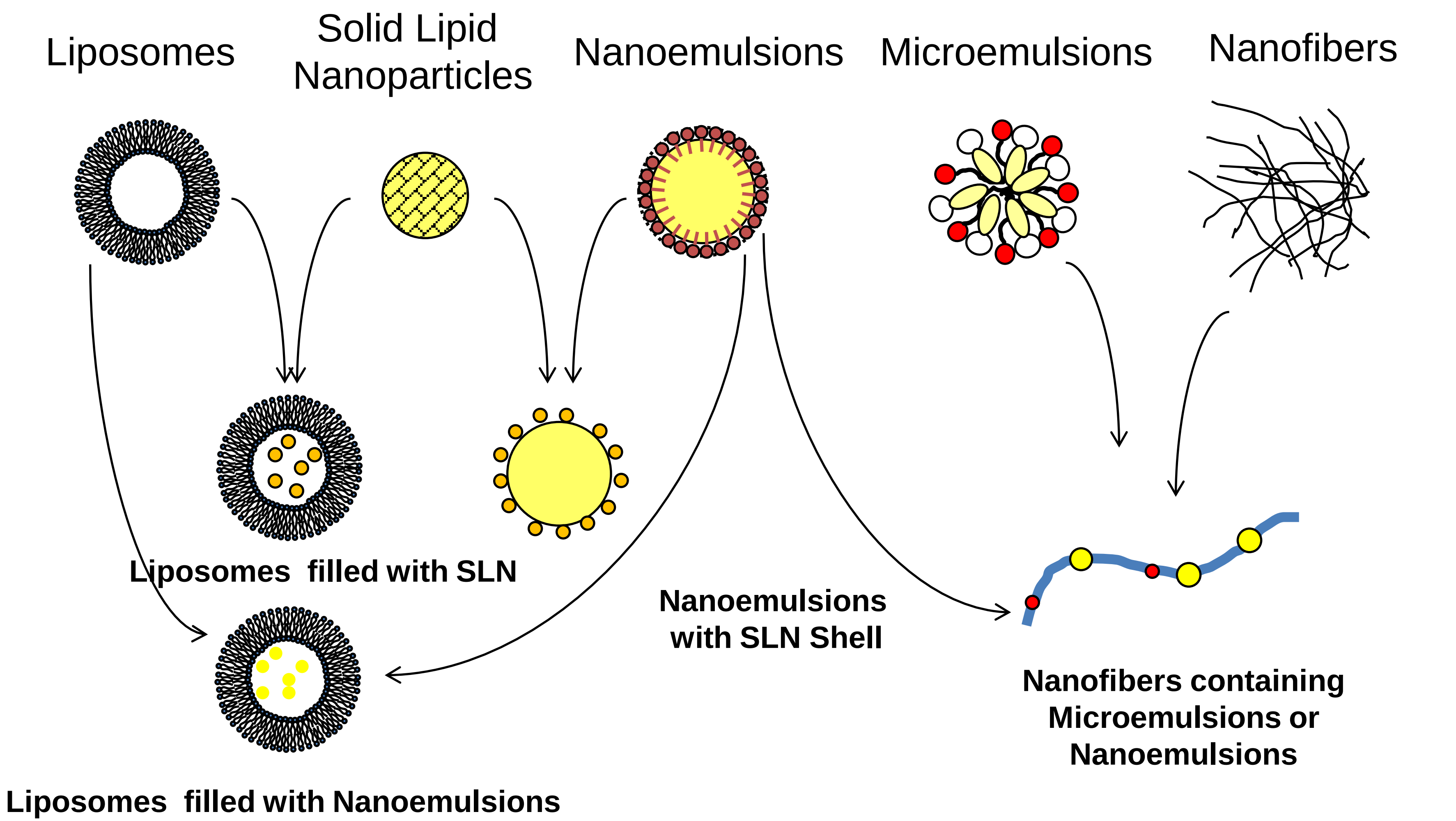
- Liquid lipid in emulsion is replaced by high melting point lipid
- Glycerides or waxes suitable
- Typical medium size ranges from 50 - 500 nm
- At small sizes, crystal structures become dependent on surfactant and size
- Highly effective carrier systems for susceptible bioactive ingrediants

TEM of SLN Preparation after 1 year storage

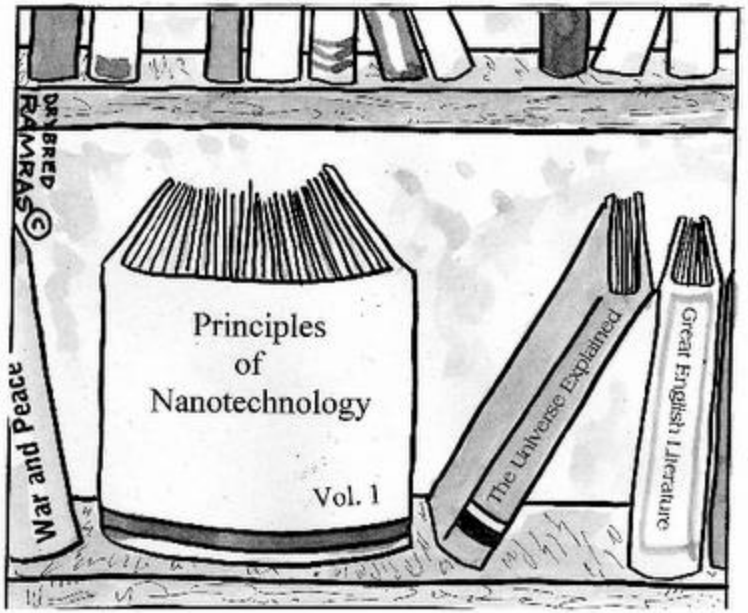


Dubes et al, European Journal of Pharmaceutics and Biopharmaceutics, 2003, Vol. 55, 279-282

The Future of the Science: Playing Lego with Molecules
- Composite Nanostructures -



Implications for Stakeholders



How does this impact the consumer and what issues will we, the stakeholders, have to wrestle with?

Implications for A World of Diminishing Resources & the Developing World

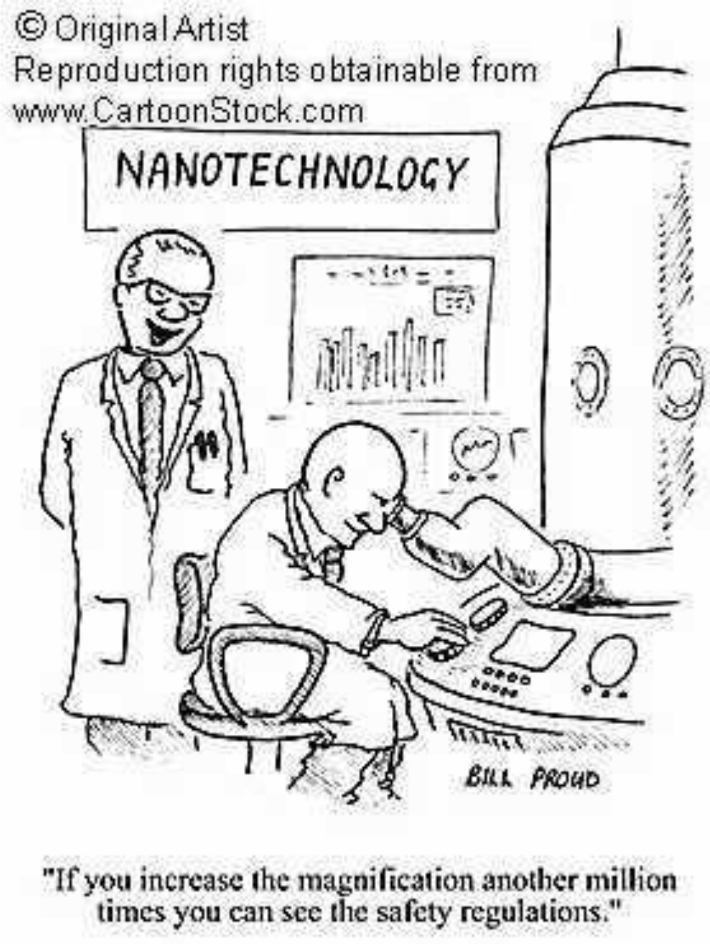
- Material production involves little labor and requires less energy due to the better use of natural processes → self-assembly or „assisted" assembly
- Improved utilization of previously underutilized resources and materials to achieve known or new functionalities
- The skill/art lies in the initial design and construction of the functional structure, and less so in the actual process.
- BUT: thermal fluctuations can introduce some randomness at very small lengthscales

Can Nanotechnology Bridge Consumer Demands and Diminishing Resources ?

- **Diminishing Resources**:
  - **Energy Savings:** Nanofabrication processes can require less energy consumption than traditional processes → substantial energy savings
  - **Waste Creation & Systainability:** Material may be more effectively used and previously not utilized materials (due to performance issues) may be functionalized to be of use (e.g. wider use of cellulose based renewable materials).
  - **Water Usage & Purification**: Improved methods for water purification, but probably little impact on overall usage
- **Consumer Demand:**
  - **Healthier Foods:** Nanoencapsulation will be a key tool to include bioactive ingredients in foods, new structures may also simulate performance of "less healthy" ingredients (e.g. fat reduction, replacement)
  - **Safer Foods:** Food safety may be enhanced through better detection methods (see later)

→ **Nanotechnology offers a technological approach to address rising consumer demand while having diminishing resources !**

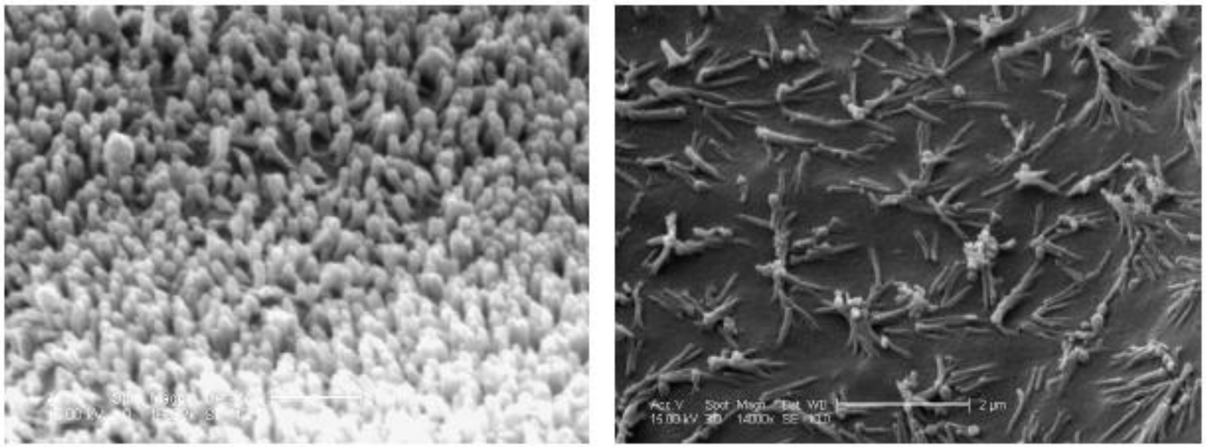
The Big Issue Though …..



- Initially - Development driven by scientists excited about the new field of science → not user driven
- Relatively rapid (maybe too rapid) uptake by some industries (not the food industry though)
- Very little **communication** to the user:
  - Benefits not clearly addressed – Is this good for the user or good for the company (it should be both)
  - Risks not properly assessed
  - Boundaries between old and new blurred → when is it nano and when is it not

This is what's scaring people..

SEM Image of Microvilli After 24h Exposure



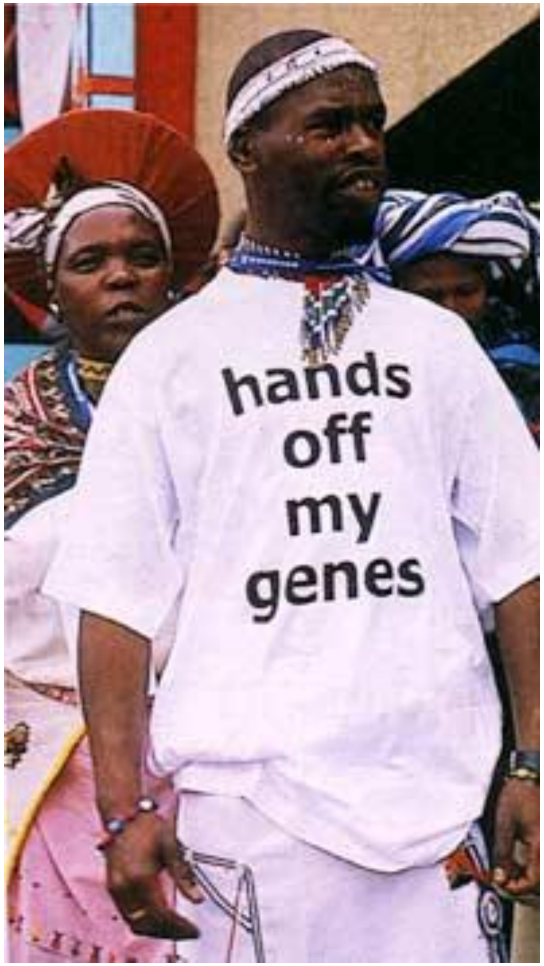
Control | 1000 ppm TiO_2

Zhang *et al*., 2007

TiO_2 flatten down the microvilli of cells

Changes in surface properties of CaCo2 cells after exposure to TiO_2 nanoparticles (40 nm)

Technology Backlash Looms Large



- Extremely high risk of repeating the mistakes of the biotech revolution
- New science was used to create new products without consumer input
- Pace was too rapid and not all stakeholders were at the same table
- **Risks and benefits** MUST be clearly communicated to the user
- Companies must weigh which of the exciting developments coming out of academia are acceptable and desirable to their customers (driver should not be cost cutting)

→ Need much more joint activities of all stakeholders, e.g. development based on clear consumer input → the science becomes part of the solution and not the problem

The Issue of Risk …

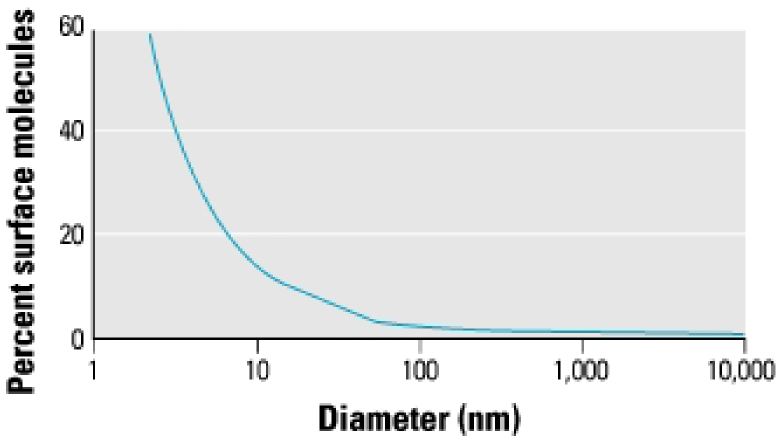


Figure 2. Surface molecules as a function of particle size. Surface molecules increase exponentially when particle size decreases < 100 nm, reflecting the importance of surface area for increased chemical and biologic activity of NSPs. The increased biologic activity can be positive and desirable (e.g., antioxidant activity, carrier capacity for therapeutics, penetration of cellular barriers), negative and undesirable (e.g., toxicity, induction of oxidative stress or of cellular dysfunction), or a mix of both. Figure courtesy of H. Fissan (personal communication).

Are nanomaterials safe?
How do we make applications of nanotechnology for foods safe?
How do we test the safety of food applications of nanotechnology?

"It is a mistake for someone to say nanoparticles are safe, and it is a mistake to say nanoparticles are dangerous. They are probably going to be somewhere in the middle, and it will depend very much on the specifics."

Vicki Colvin, Director of Center for Biological and Environmental Nanotechnology at Rice University (quoted in *Technology Review,* 2003)

Need to Establish Clear Guidelines

- Open Questions:
  - Size versus composition!!!
  - Differences between inorganic and organic (edible) nanomaterials
  - Differences between route: olfactory transport, dermal penetration → suitability of cell models??
  - The issue of the food matrix…

→ This will be the focus of next years as users will demand answers to these questions!!

Conclusions

- Rapid pace of developments in the food nanotechnology
- Transfer of nanoscience and technology to food and packaging systems led to emergence of food nanotechnology
- New science enables formulation of new food applications → significant increase in number of patents
- Driven by beneficial properties of products:
  - Improved safety/quality and health benefits (bioactives)
  - Reduced environmental impact (packaging)
  - Reduced cost and increased efficiency → has acceptance dangers
- Efforts broadening from basic research in academic institutions to applied research in companies
- BUT: much greater need to increase involvement of industry, governmental and consumer organizations → needs to happen immediately and will be the major focus of the next 10-15 years while new applications are being developed.