Evolution of Metamaterials

Akhlesh Lakhtakia

Department of Engineering Science & Mechanics
Pennsylvania State University

Materials Day 2007
Pennsylvania State University

April 11, 2007

PENNSTATE

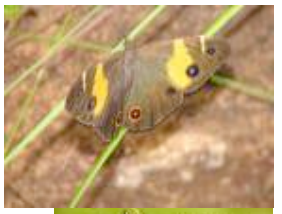
A. Lakhtakia

J.B.S. Haldane

The Creator, if he exists, has ...

A. Lakhtakia

… an inordinate fondness for beetles.



A. Lakhtakia

Engineers

have had an inordinate fondness

for

composite materials…

PENNSTATE

A. Lakhtakia

… right from the Bronze Age.

Bronze = Copper + Tin

PENNSTATE

A. Lakhtakia

Evolution of *Materials Research*

- Material Properties (< ca.1970)

PENNSTATE

A. Lakhtakia

Evolution of *Materials Research*

- Design for Functionality (ca.1980)

PENNSTATE

A. Lakhtakia

Evolution of *Materials Research*

- Design for System Performance (ca. 2000)

PENNSTATE

A. Lakhtakia

Multifunctionality

Thanks: Chuck Bakis

PENNSTATE

A. Lakhtakia

Multifunctionality

<u>Performance Requirements on the Fuselage</u>

1. Light weight (for fuel efficiency)
2. High stiffness (resistance to deformation)
3. High strength (resistance to rupture)
4. High acoustic damping (quieter cabin)
5. Low thermal conductivity (less condensation; more humid cabin)

PENNSTATE

A. Lakhtakia

Multifunctionality

Performance Requirements on the Fuselage

1. Light weight (for fuel efficiency)
2. High stiffness (resistance to deformation)
3. High strength (resistance to rupture)
4. High acoustic damping (quieter cabin)
5. Low thermal conductivity (less condensation; more humid cabin)

Future: Conducting fibers for

(i) reinforcement
(ii) antennas
(iii) environmental sensing
(iv) structural health monitoring
(iv) morphing

PENNSTATE

A. Lakhtakia

Evolution of *Materials Research*

- Material Properties (< ca.1970)
- Design for Functionality (ca.1980)
- Design for System Performance (ca. 2000)

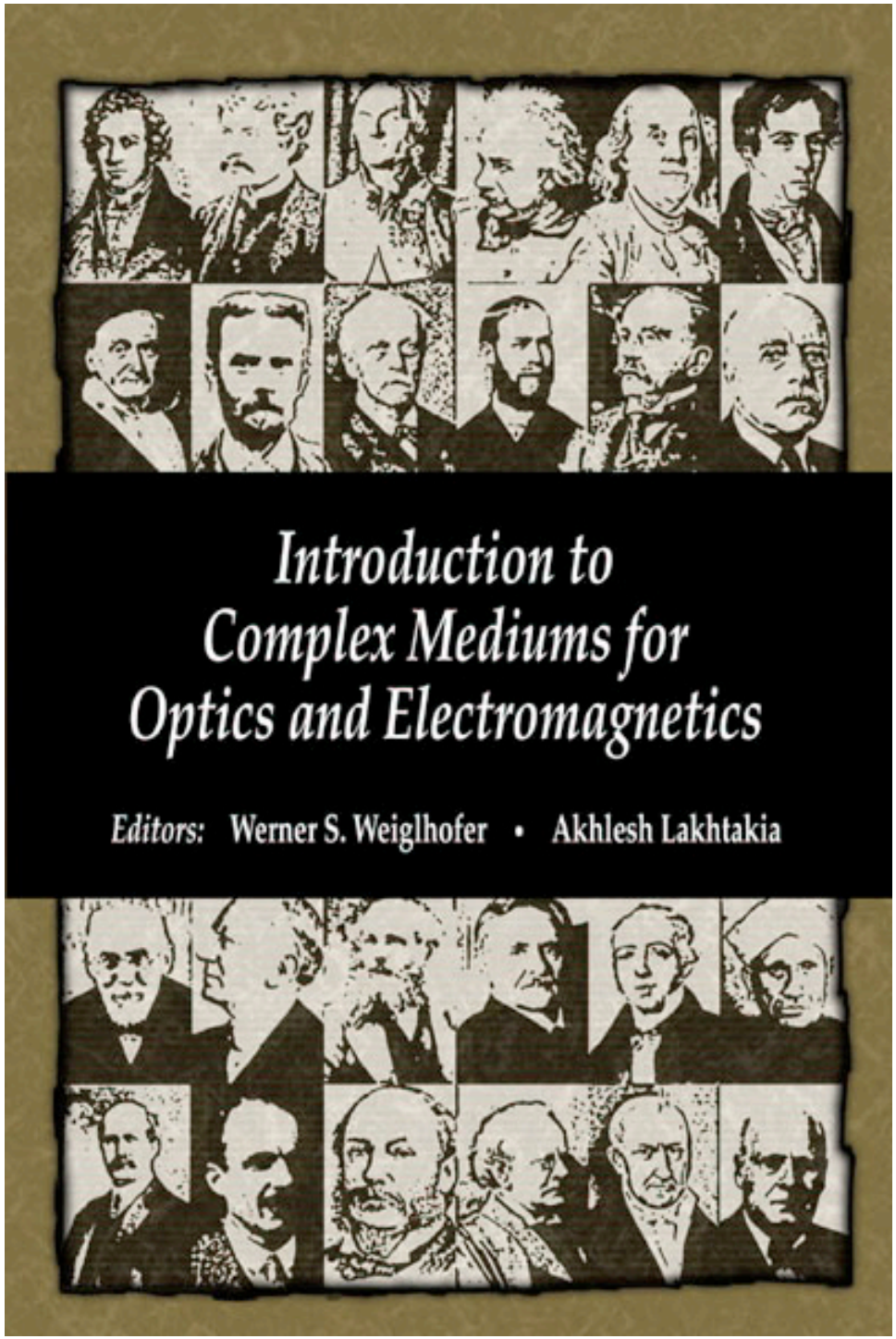
PENNSTATE

A. Lakhtakia

Metamaterials

Rodger Walser

SPIE Press (2003)



PENNSTATE

A. Lakhtakia

Walser's Definition (2001/2)

- macroscopic composites having a manmade, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation

A. Lakhtakia

Walser's Definition (2001/2)

manmade

A. Lakhtakia

Walser's Definition (2001/2)

three-dimensional

A. Lakhtakia

Walser's Definition (2001/2)

periodic

cellular

PENNSTATE

A. Lakhtakia

Walser's Definition (2001/2)

designed to
produce an optimized combination
of two or more
responses to specific excitation

A. Lakhtakia

Walser's Definition (2001/2)

not

available in nature

PENNSTATE

A. Lakhtakia

Walser's Definition (2001/2)

not

available in nature

D.G. Stavenga, Invertebrate superposition eye-structures that behave like metamaterial with negative refractive index, *JEOS-RP* **1**, 06010 (2006).

PENNSTATE

A. Lakhtakia

Walser's Definition (2001/2)

- macroscopic composites having a manmade, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation

PENNSTATE

A. Lakhtakia

Working Definition

'Metamaterial'

- composite which exhibits properties:
  - * not observed in constituents

    or

  - * enhanced relative to properties of constituents

PENNSTATE

A. Lakhtakia

Composite Materials with Viscoelastic Stiffness Greater Than Diamond

T. Jaglinski,[1] D. Kochmann,[2] D. Stone,[3] R. S. Lakes[4]*

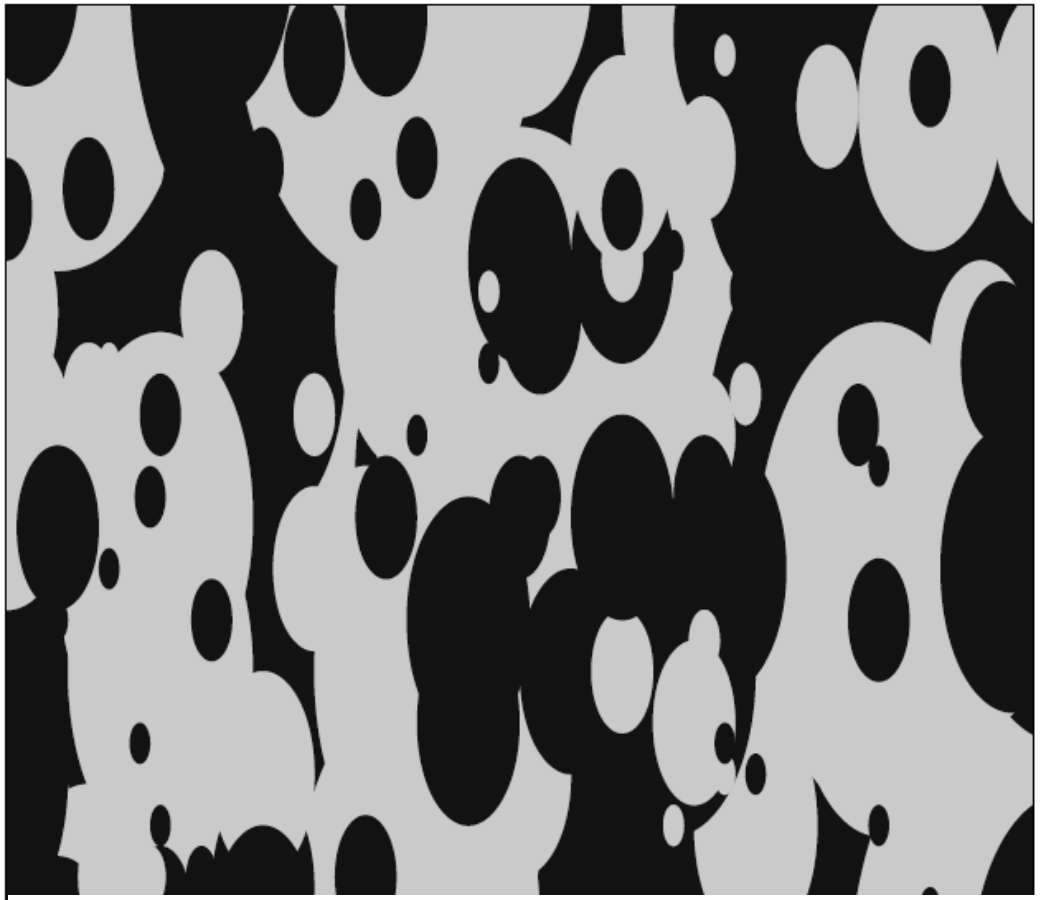
We show that composite materials can exhibit a viscoelastic modulus (Young's modulus) that is far greater than that of either constituent. The modulus, but not the strength, of the composite was observed to be substantially greater than that of diamond. These composites contain barium-titanate inclusions, which undergo a volume-change phase transformation if they are not constrained. In the composite, the inclusions are partially constrained by the surrounding metal matrix. The constraint stabilizes the negative bulk modulus (inverse compressibility) of the inclusions. This negative modulus arises from stored elastic energy in the inclusions, in contrast to periodic composite metamaterials that exhibit negative refraction by inertial resonant effects. Conventional composites with positive-stiffness constituents have aggregate properties bounded by a weighted average of constituent properties; their modulus cannot exceed that of the stiffest constituent.

2 FEBRUARY 2007 VOL 315 **SCIENCE**

PENNSTATE

A. Lakhtakia

Examples:
Particulate Composite Materials with ellipsoidal inclusions



$\lambda \gg$ inclusion size

PENNSTATE

A. Lakhtakia

Homogenizable Metamaterials

- Enhancement of group velocity
- Enhancement of nonlinearity
- Voigt wave propagation
- Bianisotropy
- Negative phase velocity

http://www.esm.psu.edu/~axl4/lakhtakia/documents/Mackay_06_6MRI.pdf

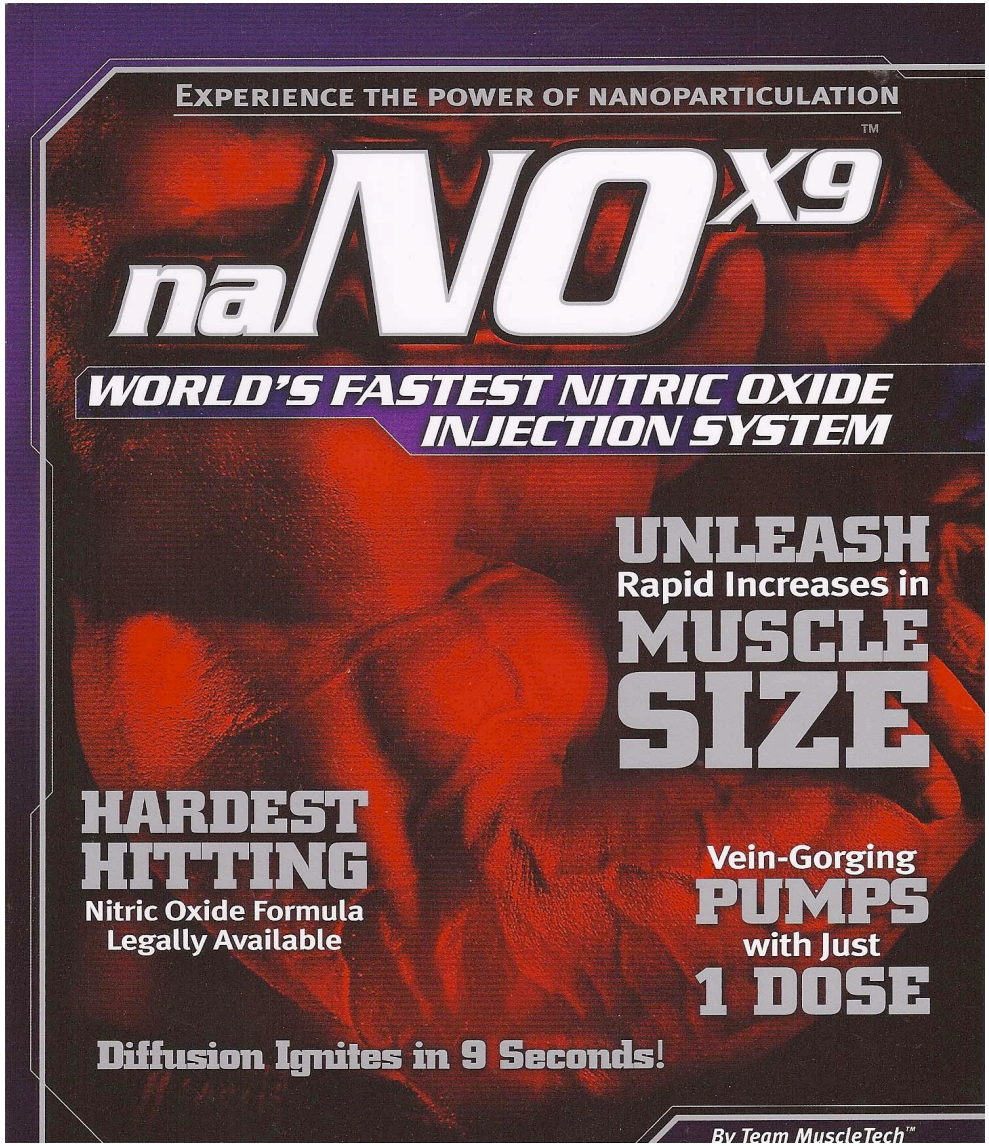
What Next?

A. Lakhtakia

Nanotechnology, of course!

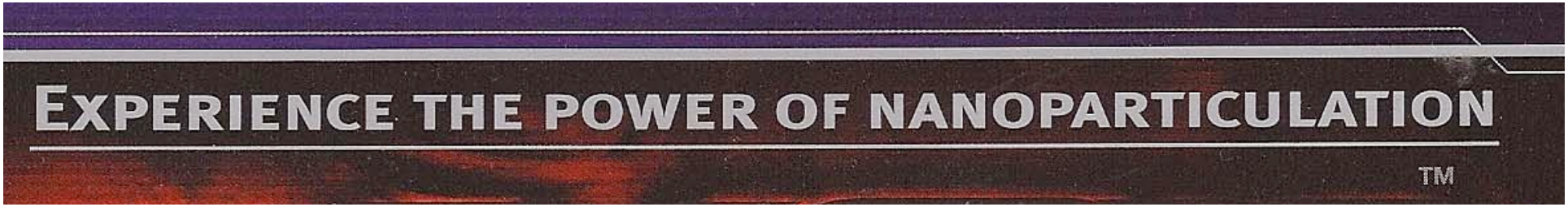
PENNSTATE

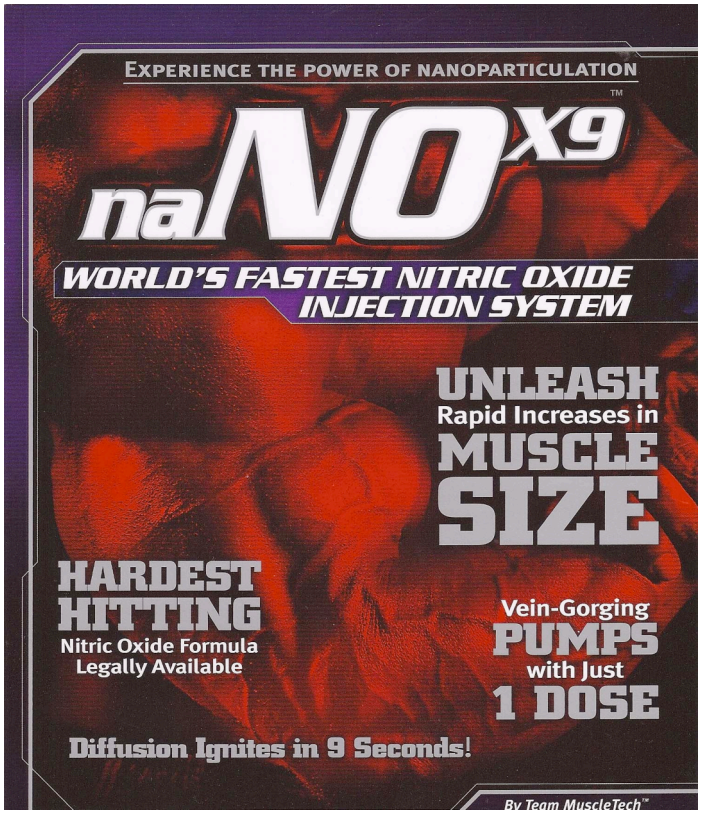
A. Lakhtakia



PENNSTATE

A. Lakhtakia





A. Lakhtakia

The Case for Nanotechnological Metamaterials

A. Lakhtakia

The Case for Nanotechnological Metamaterials:

CELLULARITY

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Morphology

Performance

Cellularity

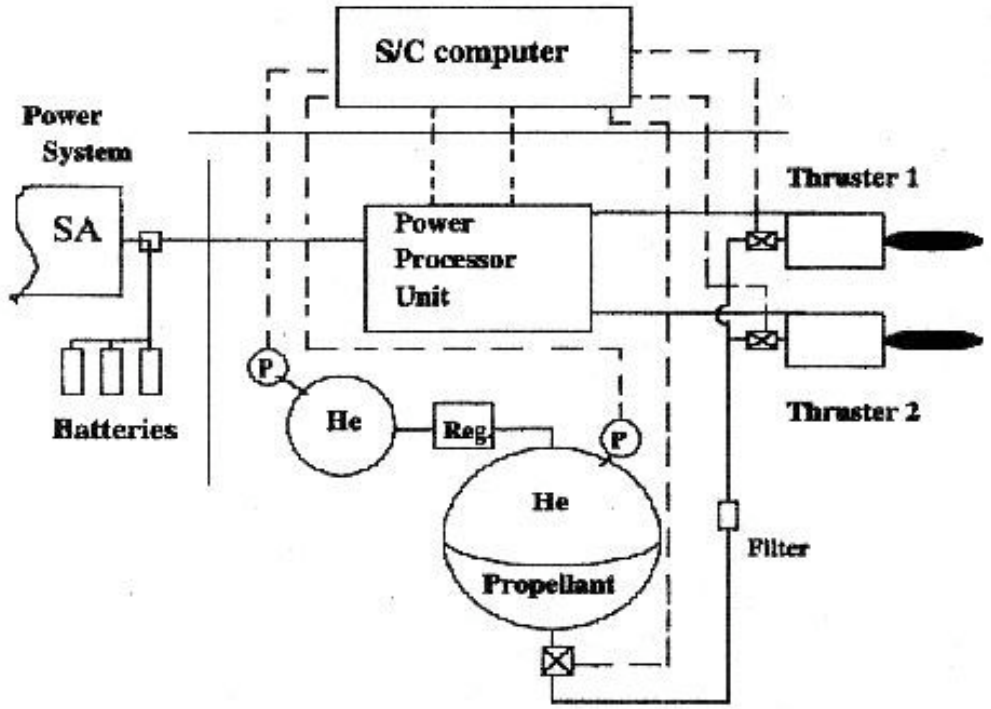
Multifunctionality

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Multi-component system = Assembly of different components



PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

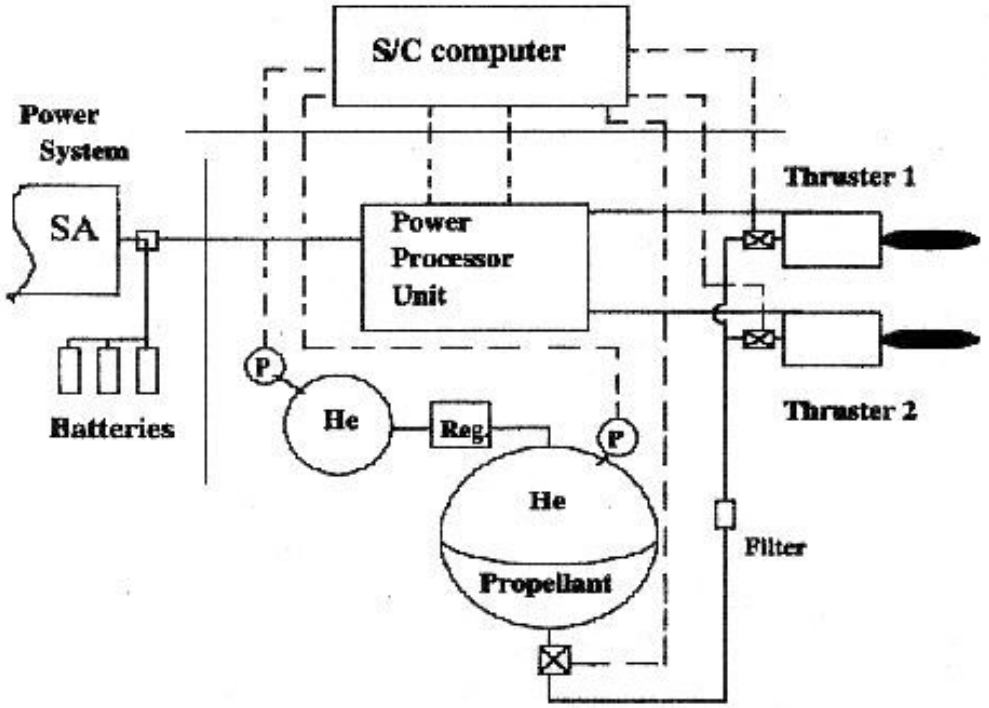
Multi-component system = Assembly of different components

Component:

Simple action

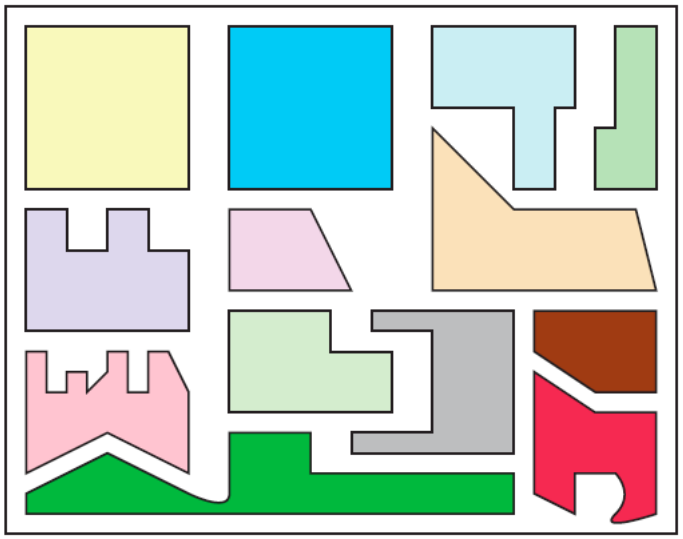
Assembly of components:

Complex action



Nanotechnological Metamaterials

Supercell

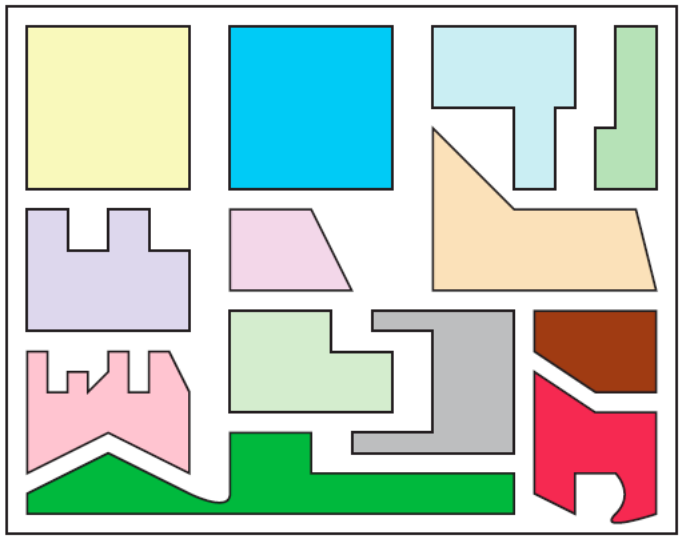


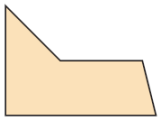
PENNSTATE

Nanotechnological Metamaterials

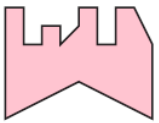
A. Lakhtakia

Supercell



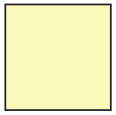


RFcomm cell



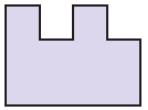
IRcomm cell

Energy harvesting cell

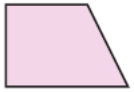


Energy storage cell

Energy distributor cell



Chemisensor cell



Force-sensor cell

Shape-changer cell

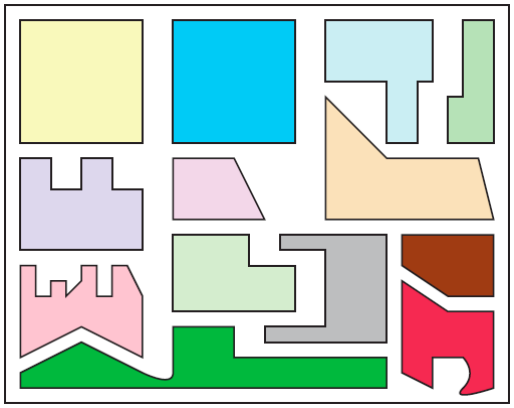
Light-source cell

PENNSTATE

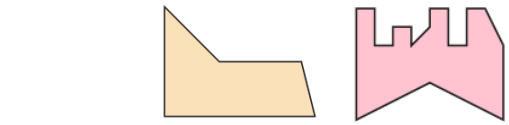
A. Lakhtakia

Nanotechnological Metamaterials

Supercell

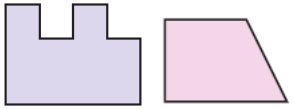


Cellular Phenotypes



Communication cells

Energy cells



Sensor cells

Actuator cells

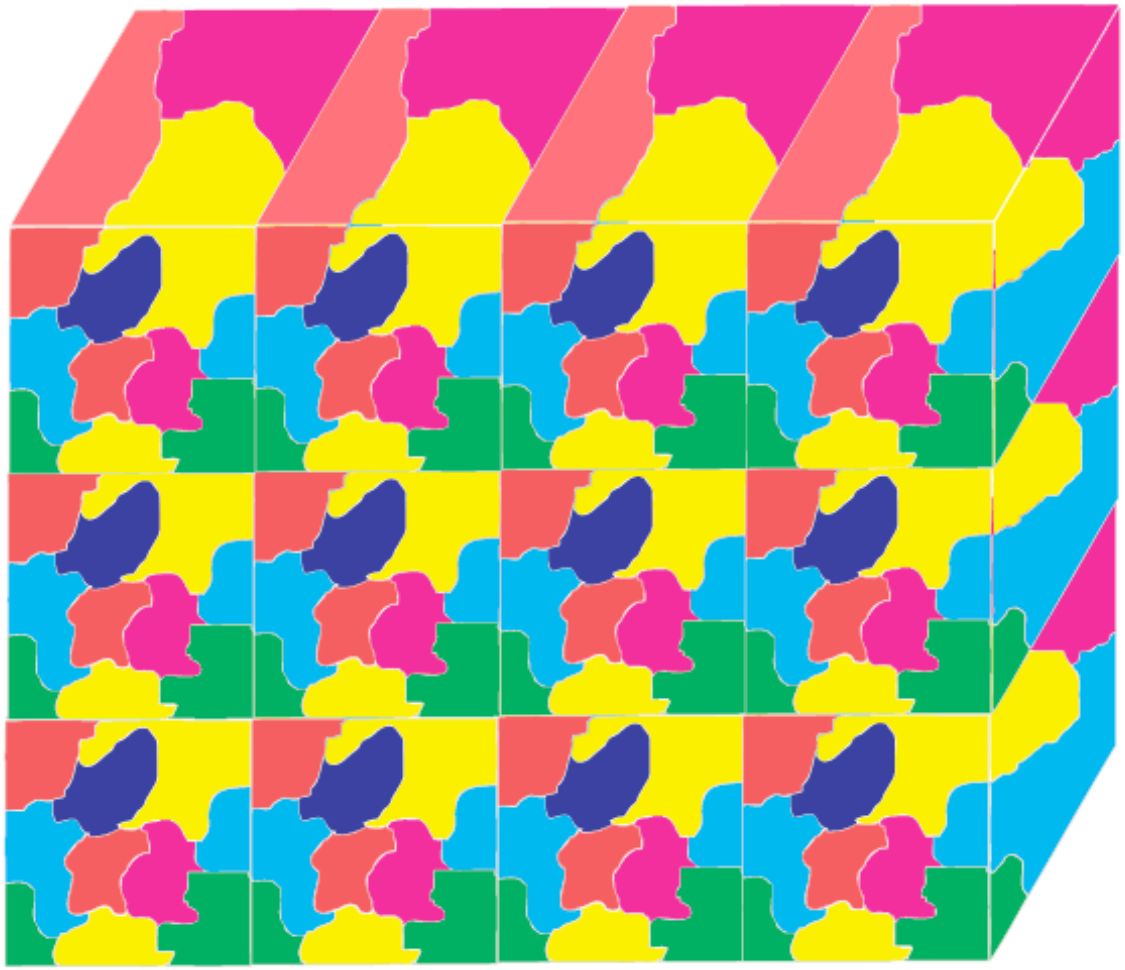
Light cells

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Periodic Arrangement of Supercells

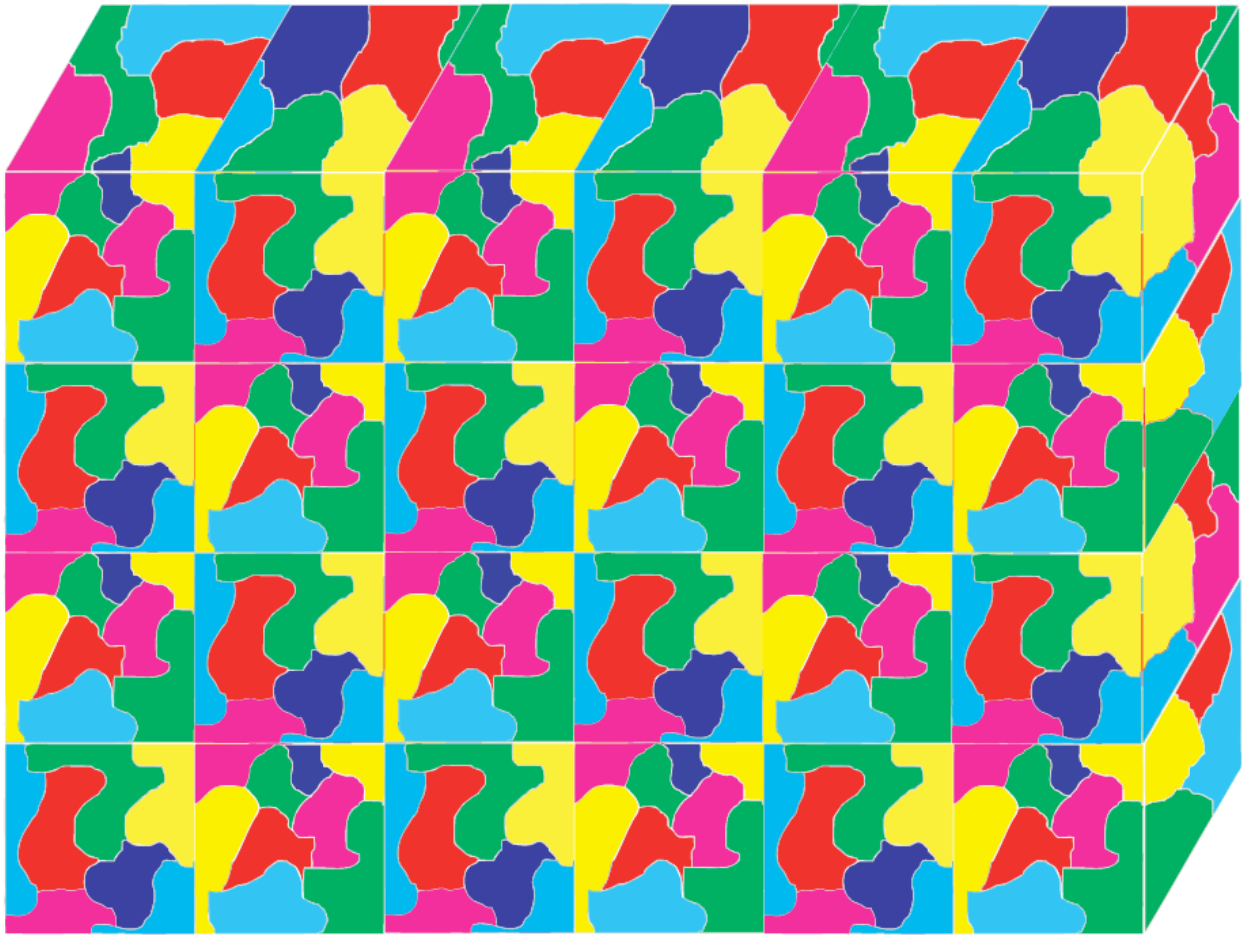


PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Superlattice of Supercells

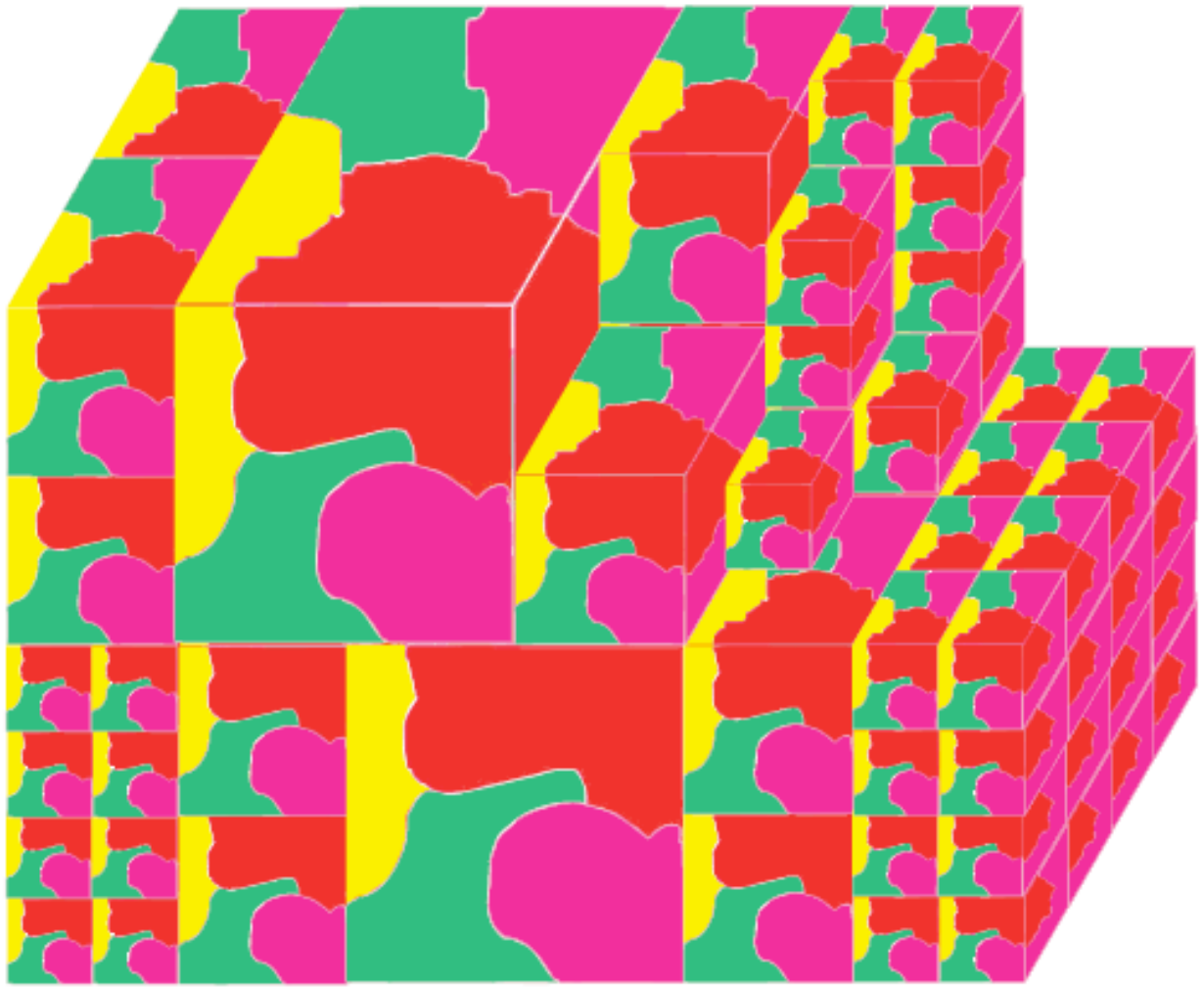


PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Fractal Arrangement of Supercells

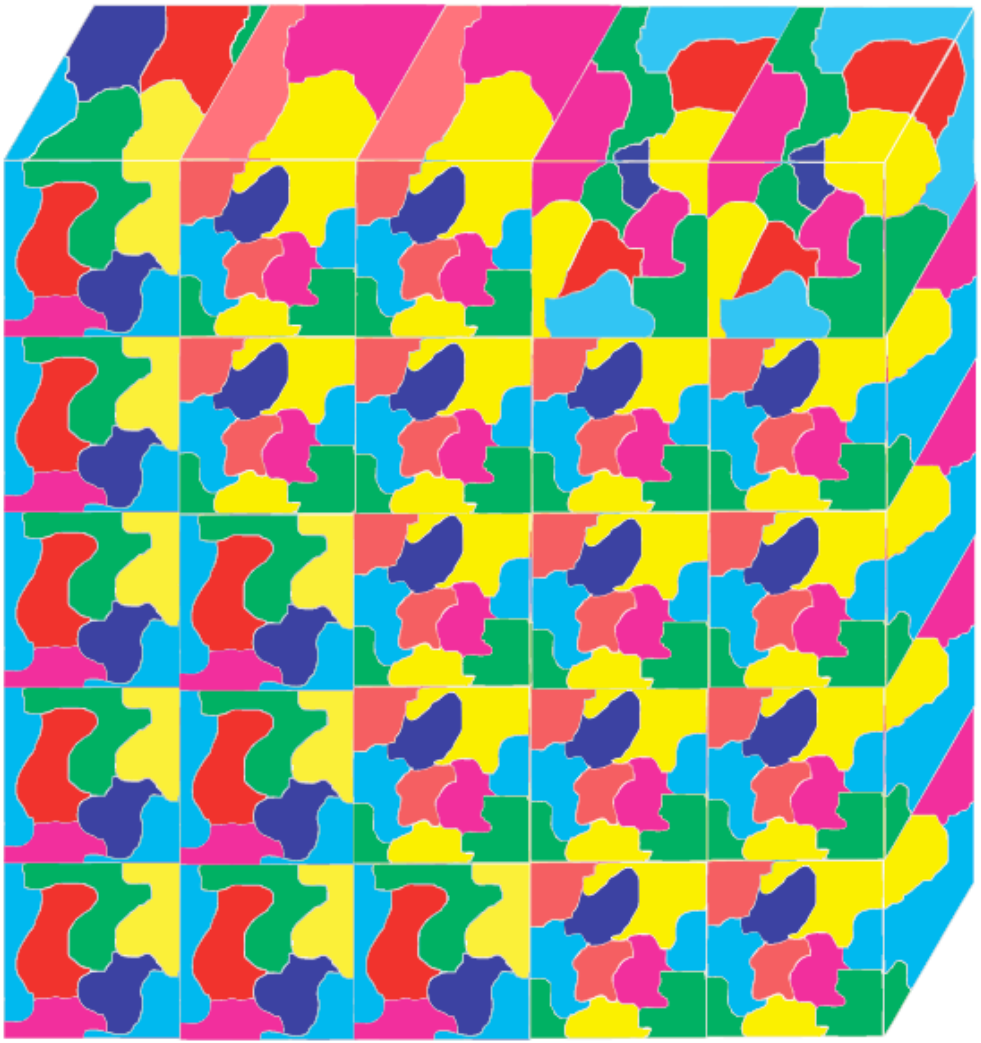


PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Functionally Graded Arrangement of Supercells

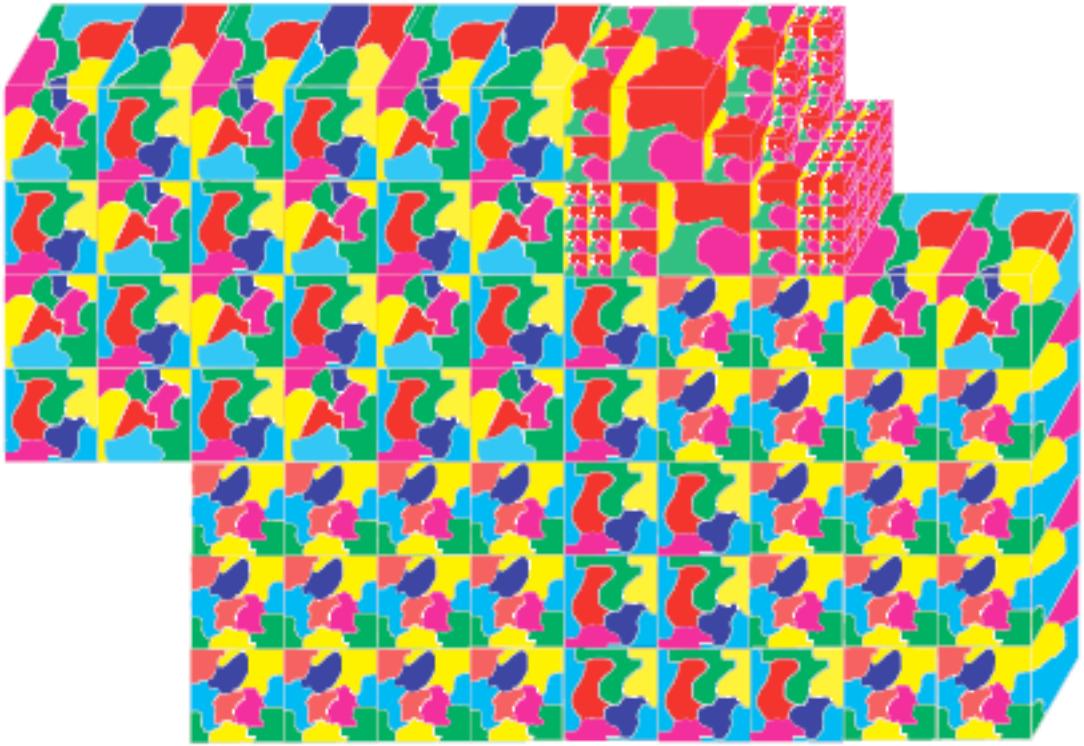


PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Supercellular Architecture

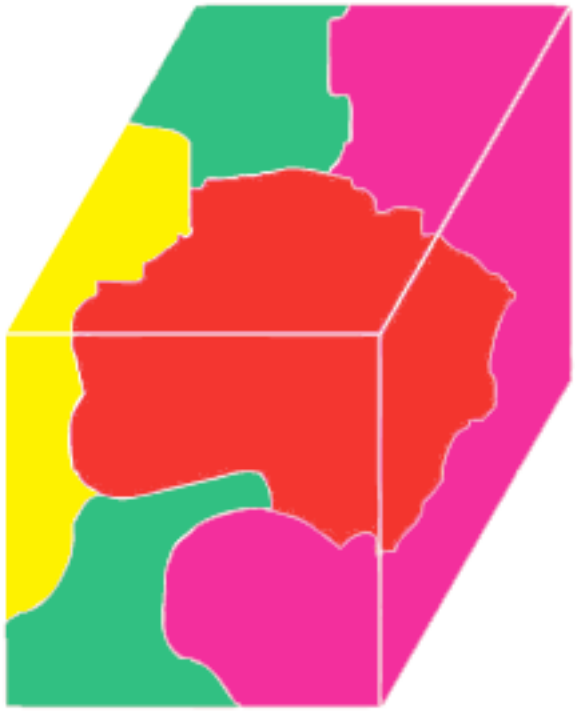


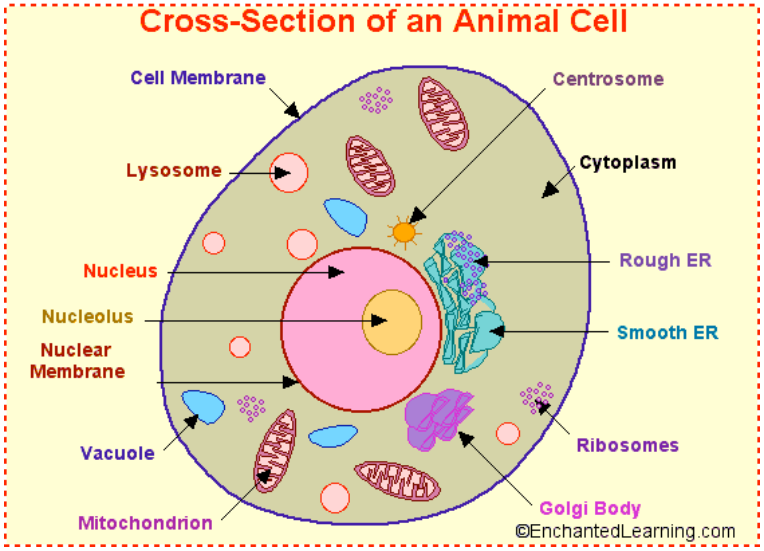
PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Biomimesis



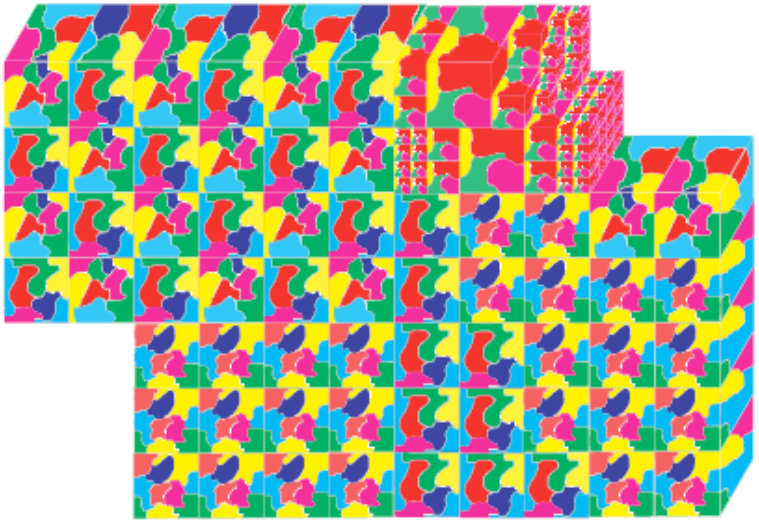


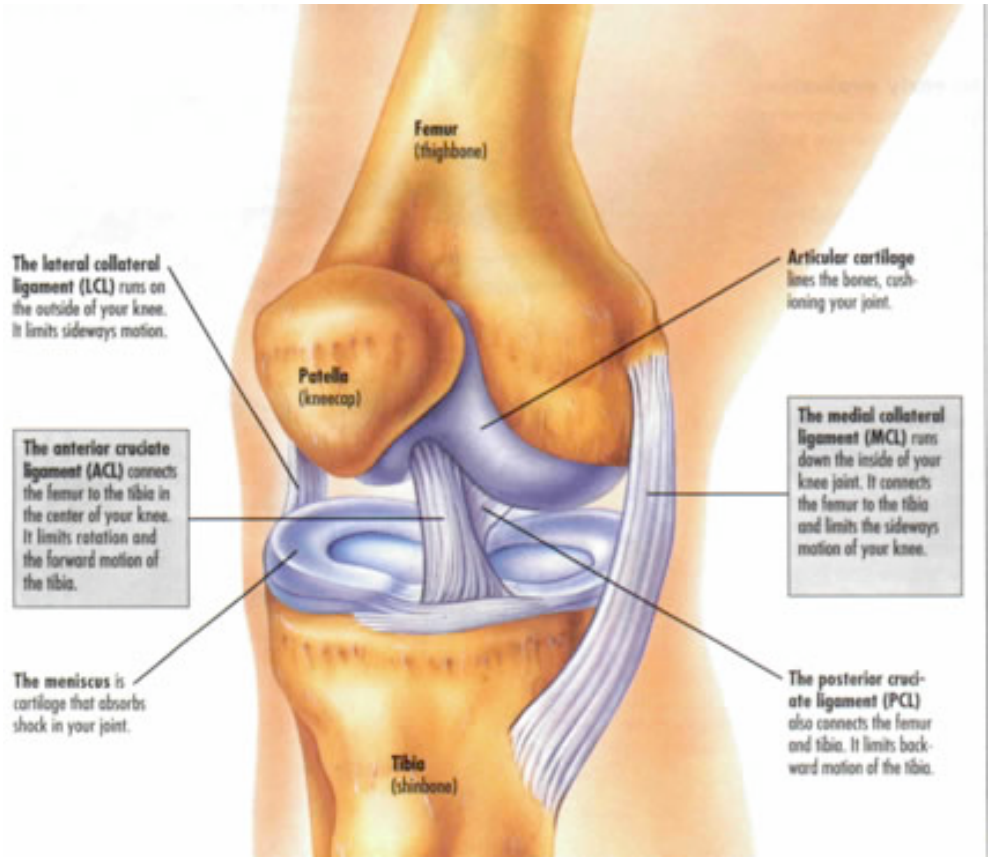
PENNSTATE

Nanotechnological Metamaterials

A. Lakhtakia

Biomimesis





PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Fabrication

1. Self-assembly
2. Positional assembly
3. Lithography
4. Etching
5. Ink-jet printing
6. ….
7. ….
8. Hybrid techniques

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Copyright: Disney World

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

Copyright: Disney World

1. Nanophysics ≠ Bulk physics

- *Danger in scaling!*

2. Interaction between cells

- *Incidental*
  - Serendipitous
  - Deleterious

3. Defects

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

in a car

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

in a car

Exterior Skin

- Mechanical stiffness
- Shock-absorbing crumple zones
- Maintenance of internal atmosphere

- Harvesting of energy
  - * sun
  - * overhead lights
  - * wireless sources

- Collision-avoidance sensors

- Self-healing paintwork

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

in a car

Front Windscreen

- Mechanical stiffness
- Shatter-safety
- Visibility

- Defrosting
- Sunshine reduction
- Instrument displays

- Magnification zones

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

in a car

Dashboard

- Moldings for receptacles
- Airbags

- Antennas for communications
  - * GPS
  - * Telephones
  - * Appliances at home/work

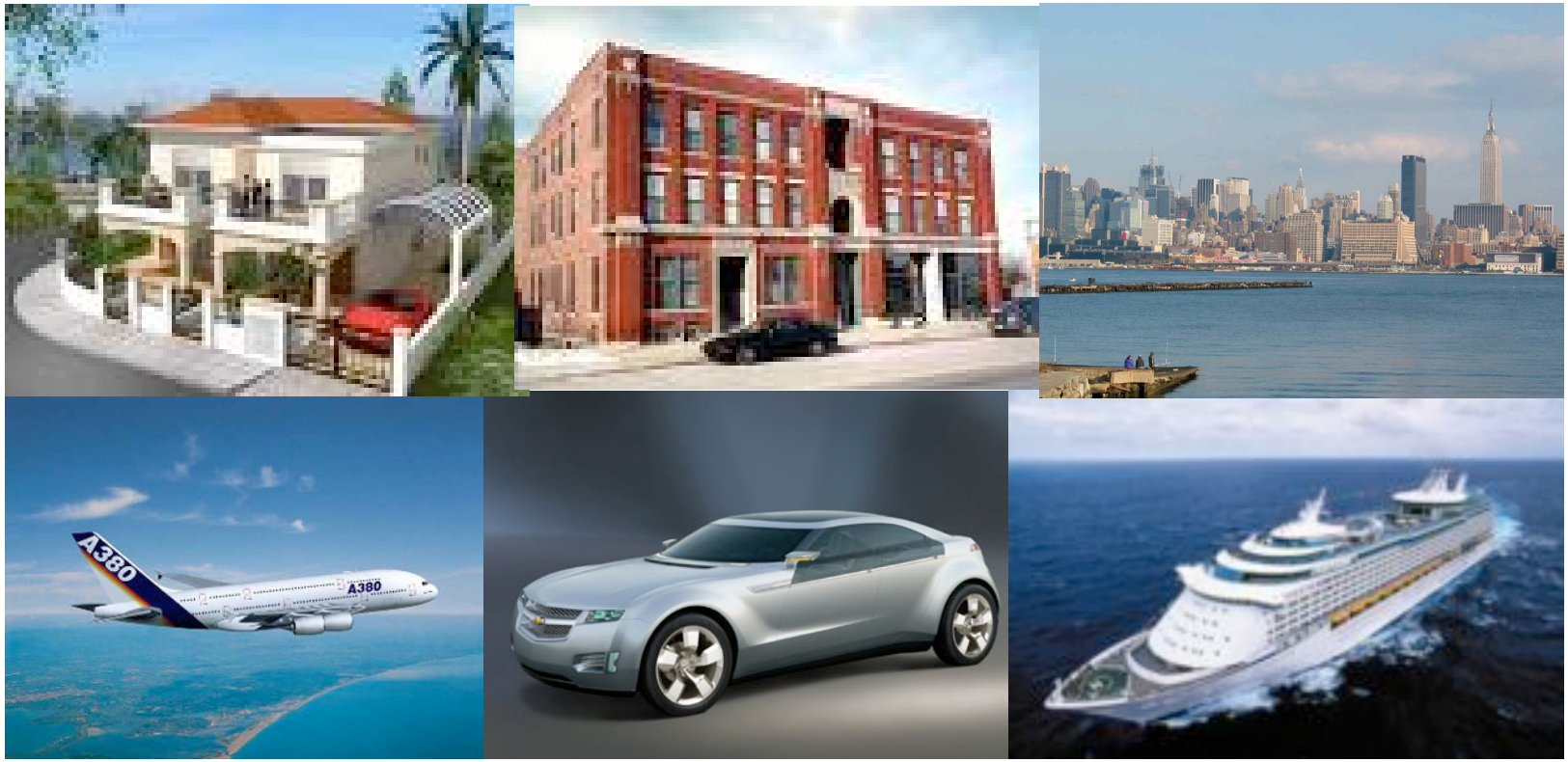
- Biosensors for Driver's Condition

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

everywhere



A. Lakhtakia

Nanotechnological Metamaterials

everywhere

Intelligent Infrastructure

for

Living

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

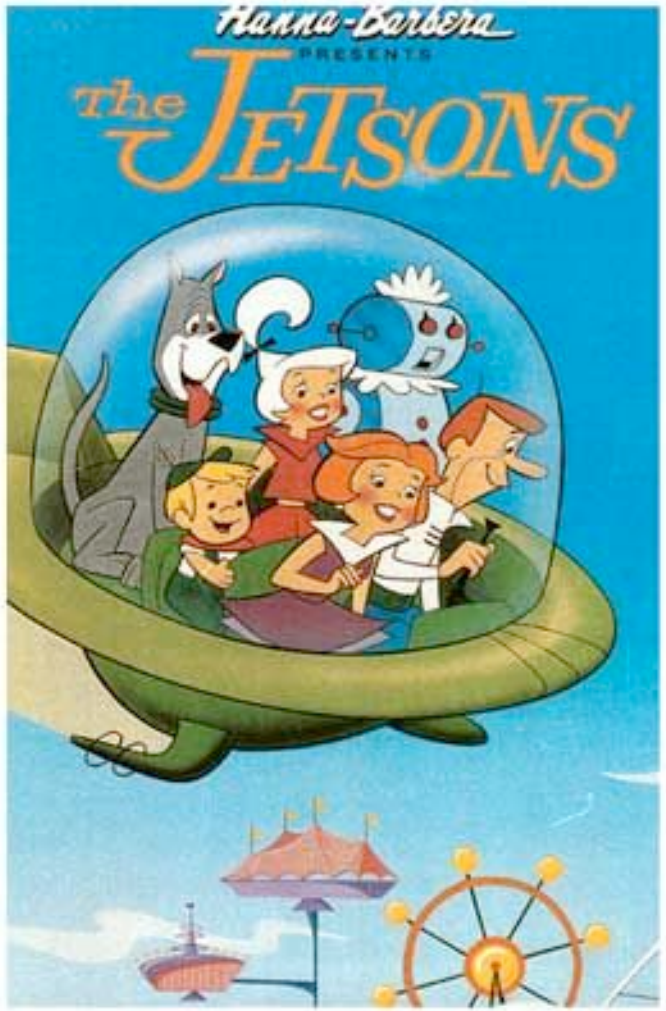
everywhere

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

everywhere



Nanotechnological Metamaterials

everywhere

The Downside

A. Lakhtakia

Nanotechnological Metamaterials

everywhere

The Downside

1. Social Footprint
    * Public health and safety
    * Worker health and safety
    * Privacy

2. Ecological Footprint
    * Waste management
    * Air, soil, water contamination

PENNSTATE

A. Lakhtakia

Nanotechnological Metamaterials

everywhere

Management of the Downside

Researchers' Responsibilities

1. Scenario Planning
2. Impact Studies
3. Public Education


"That's all Folks!"