MECHANICS OF MULTIFUNCTIONAL MATERIALS & MICROSYSTEMS

Integrity ★ Service ★ Excellence

9 March 2012

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Program Manager
AFOSR/RSA
Air Force Research Laboratory

Report Documentation Page

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NAME: ***B. L. ("Les") Lee***

BRIEF DESCRIPTION OF PORTFOLIO:

Basic science for integration of emerging materials and micro-devices into future Air Force systems requiring multi-functional design

LIST OF SUB-AREAS:

Fundamentals of Mechanics of Materials;
Life Prediction (Materials & Micro-devices);
Sensing, Detection & Diagnosis;
Multifunctional Design of Autonomic Systems;
Multifunctional Design of Reconfigurable Systems;
Self-Healing & Remediation;
Self-Cooling & Thermal Management;
Energy Management for Self-Sustaining Systems;
Actuation & Threat Neutralization;
Engineered Nanomaterials

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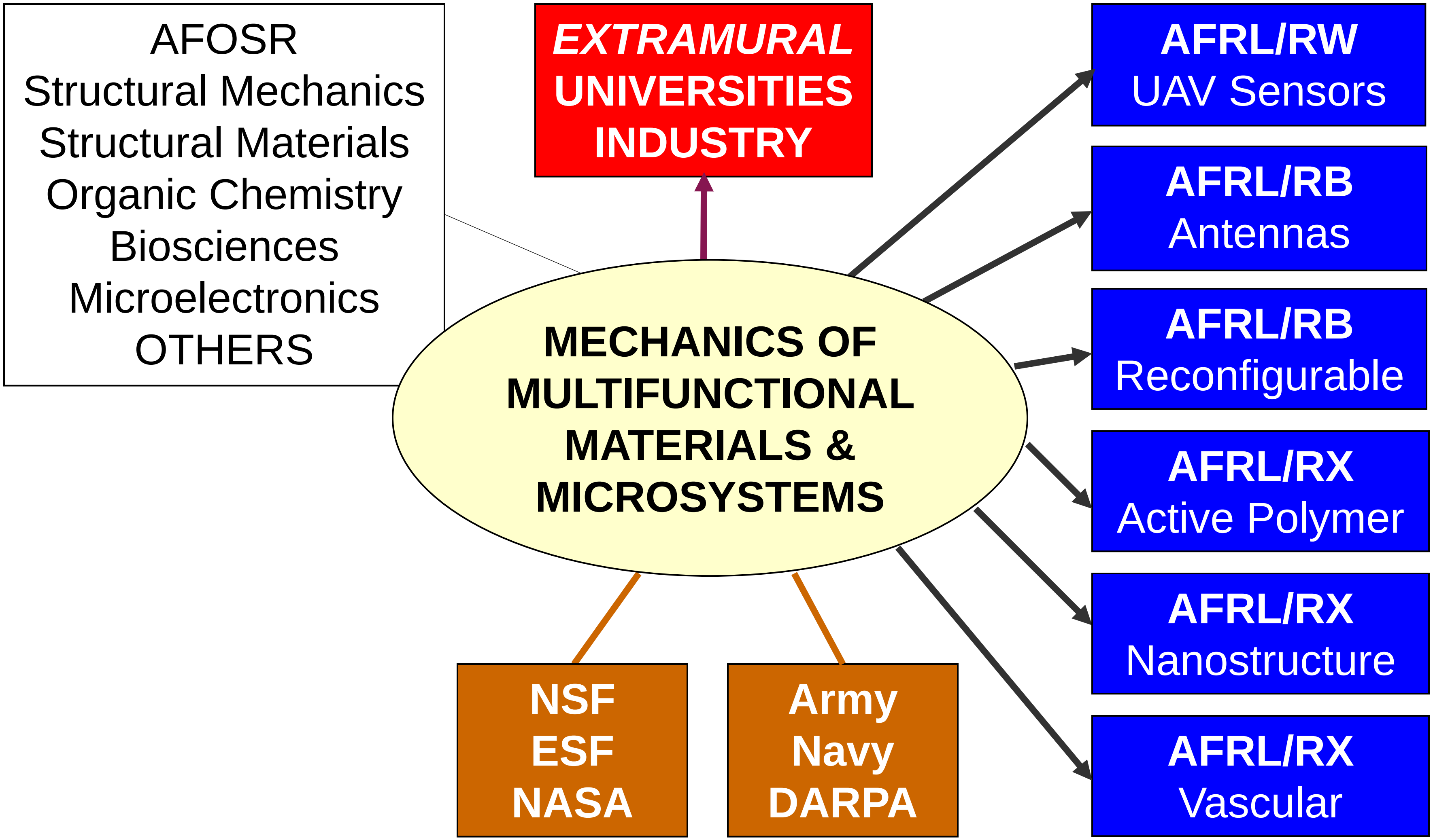
Self-Healing & Remediation; ↘
Self-Cooling & Thermal Management; →
Energy Management for Self-Sustaining Systems; ↘
Actuation & Threat Neutralization; ↗
Engineered Nanomaterials ↘

SCIENTIFIC CHALLENGE

- **Self-healable or in-situ remendable structural materials** ***(1st-ever program; world lead)***
- **Microvascular composites for continuous self-healing and self-cooling systems** ***(1st-ever program; world lead)***
- **Structural integration of energy harvest/storage capabilities** ***(1st-ever program on structurally integrated multiple energy harvest capabilities; DoD lead)***
- **Neurological system-inspired sensing/diagnosis/ actuation network** ***(pot'l world lead)***
- **Mechanized material systems and micro-devices for reconfigurable structures** ***(DoD lead)***
- **Experimental nano-mechanics** ***(DoD lead)***
- **Active materials for threat neutralization** ***(planned)***

PROGRAM INTERACTION



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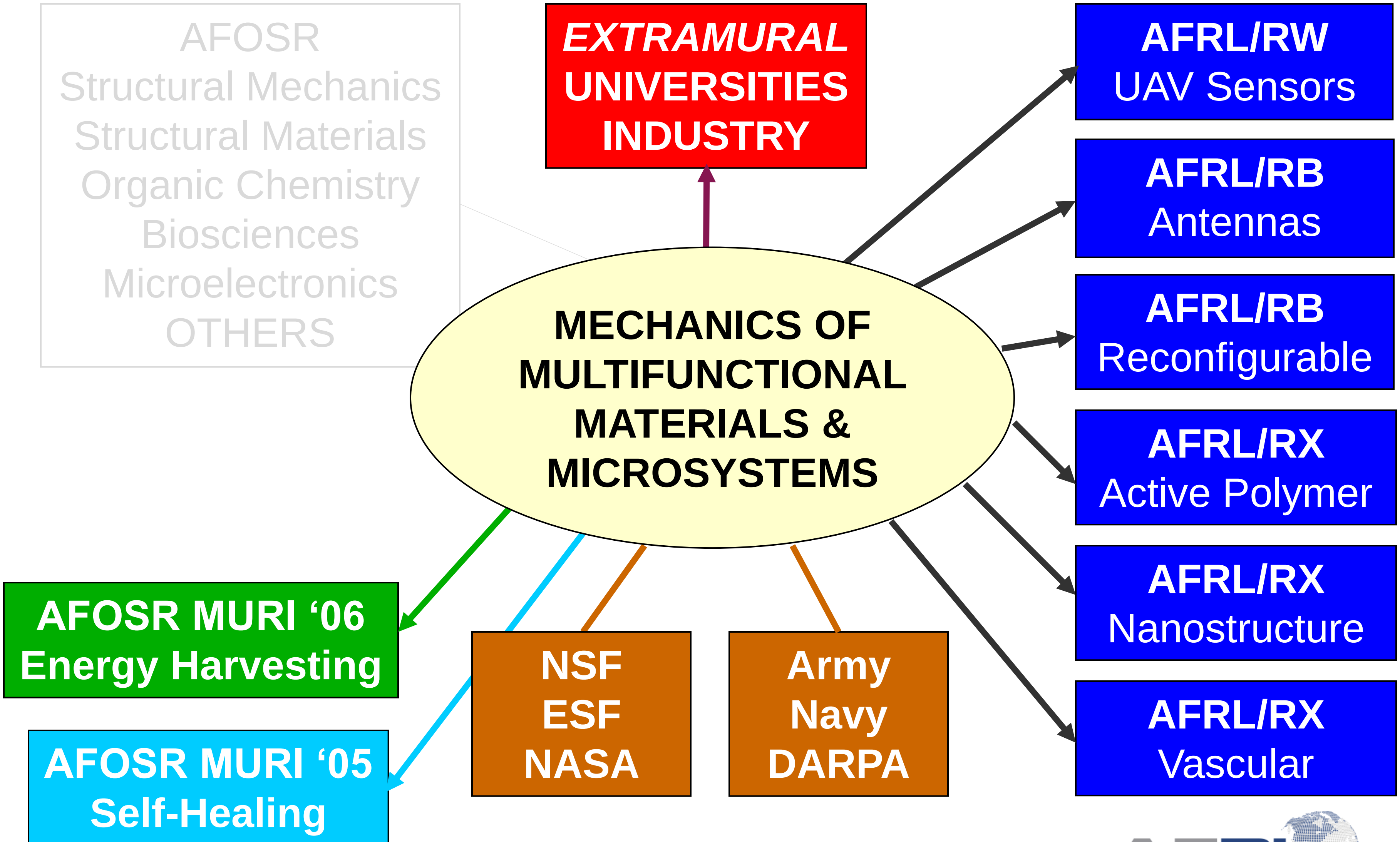

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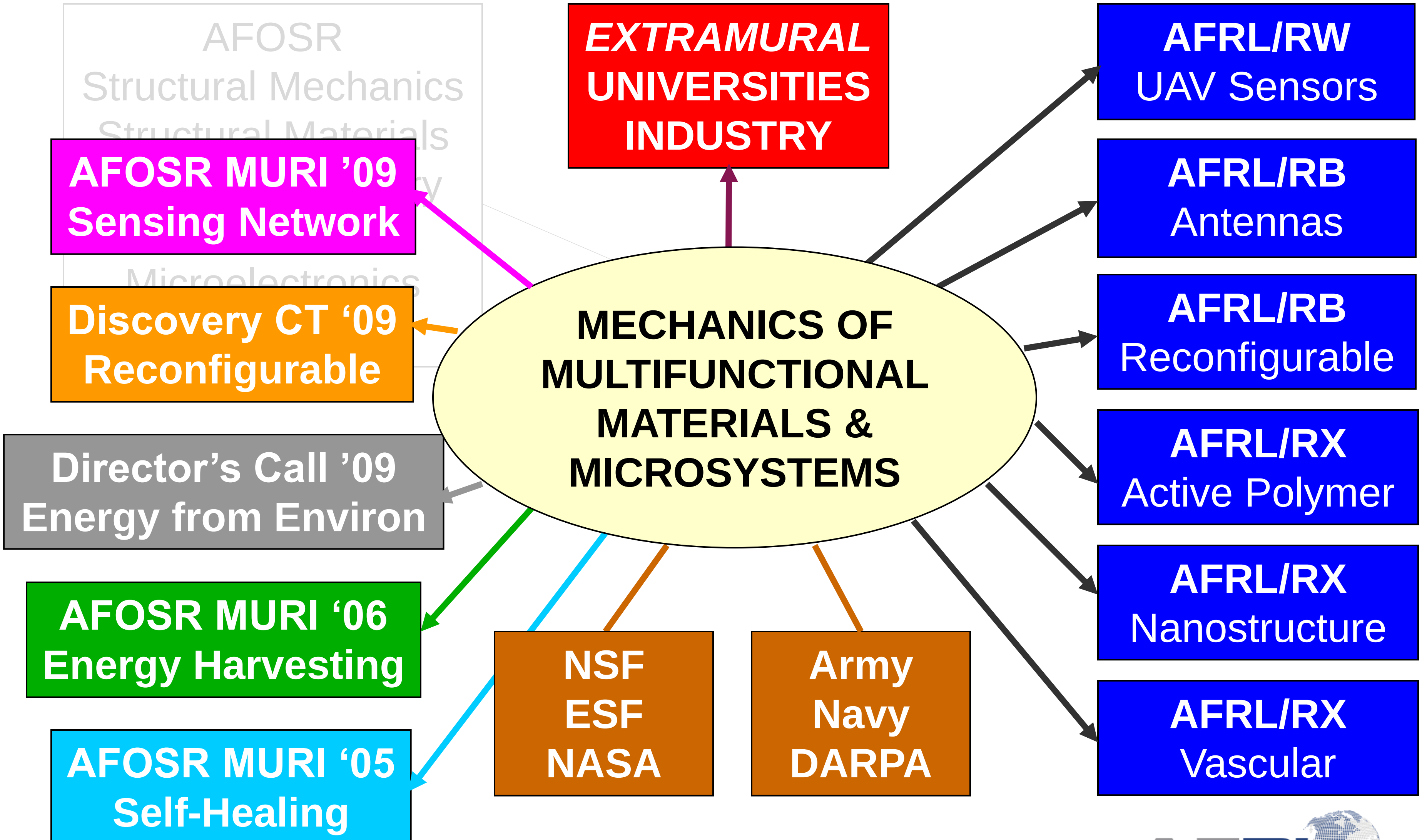

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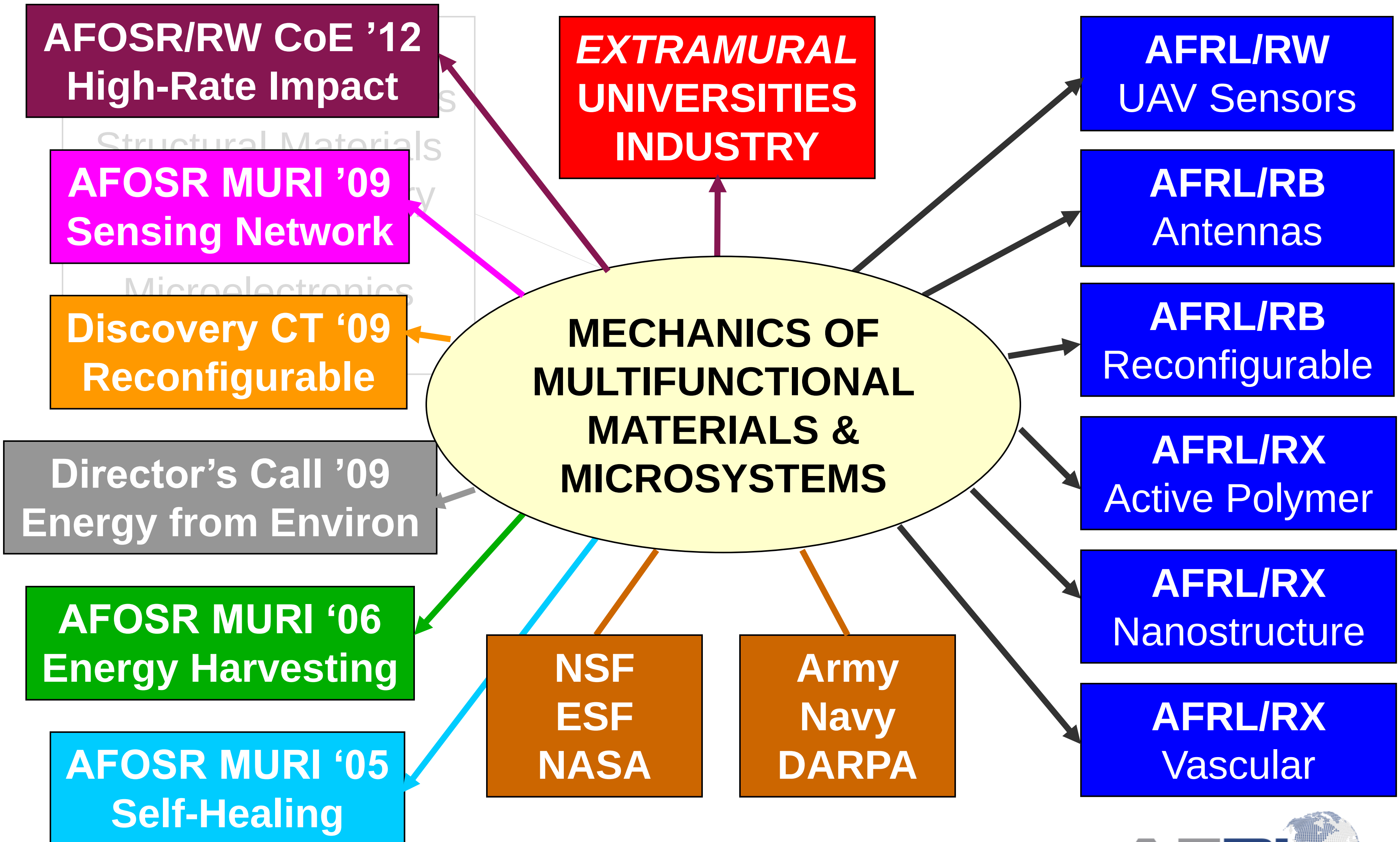

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Engineered Nanomaterials

***PI's** & Co-PI's:*

John Kieffer (U Mich)
Ioannis Chasiotis (UIUC)
David Kisailus (UC Riverside)
Pablo Zavattieri (Purdue U)
Liping Liu (Rutgers U)^
G. Ravichandran (Caltech)*
*Jose Andrade (Caltech)**
*Kaushik Bhattacharya (Caltech)**
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^ YIP; * CoE

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BRIEF DES

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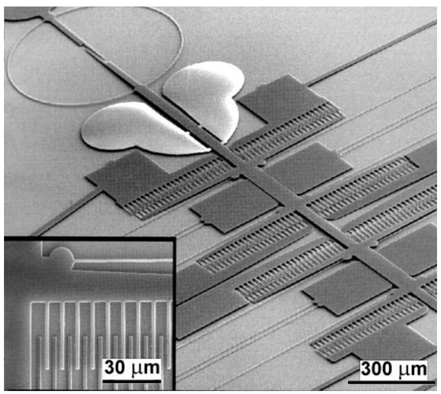
Subject:	***PI's** & Co-PI's:*
< ***Multi-scale Simulation of Interfacial Phenomena***	***John Kieffer (U Mich)***
Deformation & Fracture of Silicon for MEMS	***Ioannis Chasiotis (UIUC)***
> ***Damage-tolerant Biological Composites***	***David Kisailus (UC Riverside)***
	Pablo Zavattieri (Purdue U)
> ***Designing Structures for Functional Materials***	***Liping Liu (Rutgers U)^***
> ***High-rate Physics of Heterogeneous Materials***	***G. Ravichandran (Caltech)****
	*Jose Andrade (Caltech)**
	*Kaushik Bhattacharya (Caltech)**
	*Chiara Daraio (Caltech)**
	*Michael Ortiz (Caltech)**
	*Chris Lynch (UCLA)**
	*Greg Carman (UCLA)**
> New**; **< Concluded	***^ YIP**; *** CoE***

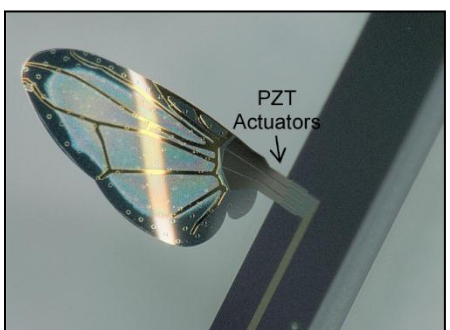
FRACTURE OF MEMS MATERIALS
(UIUC: Chasiotis)

Polycrystalline silicon is most widely used for MEMS

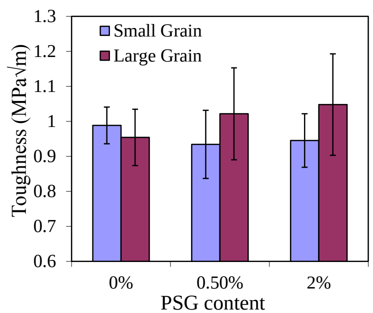
- Experiments (bi-crystal Chevron) show the role of **grain structure** in fracture of polysilicon.
- Fracture of polysilicon is **intra-granular** due to high grain boundary strength.

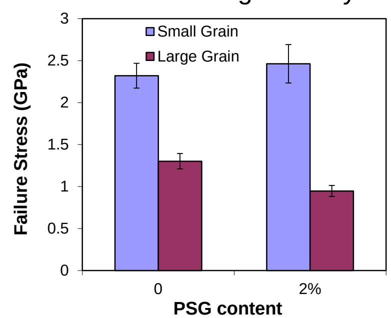


PZT thin film bimorph actuates a millimeter scale wing for MAV

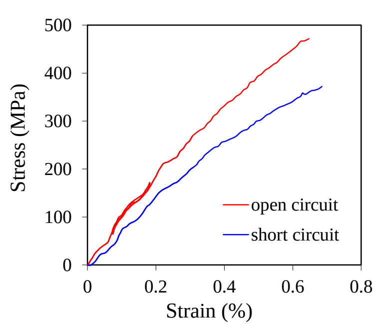


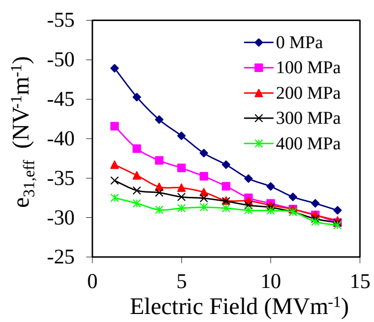
- Mode I fracture toughness of **large grain polysilicon** increased with the amount of Phosphorus **doping**. Dopants at grain boundaries may allow for **local crack deflection**.
- The fracture strength of **"laminated" small grain polysilicon** ***was 80-150% higher*** than large grain polysilicon with doping playing a secondary role in fracture strength. Fabrication of polysilicon in laminate form reduced the **flaw size** significantly.



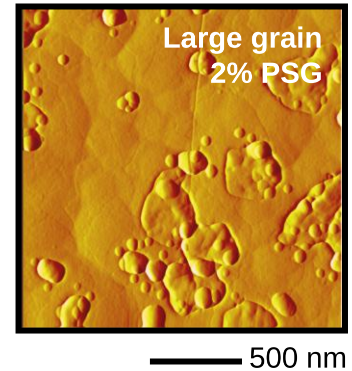


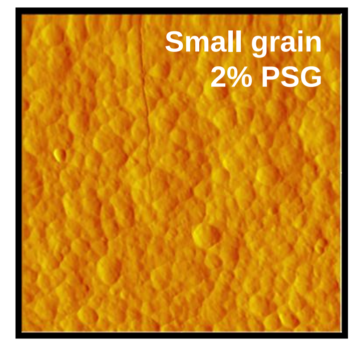
- The modulus and tensile strength of **PZT films** for MEMS were measured for the first time. They were ***30% smaller under short circuit conditions*** as opposed to open circuit conditions.
- The high bias voltage **electroactive coefficient** varied nonlinearly with the electric field, but it ***became independent of the applied field at high pre-stress values***.



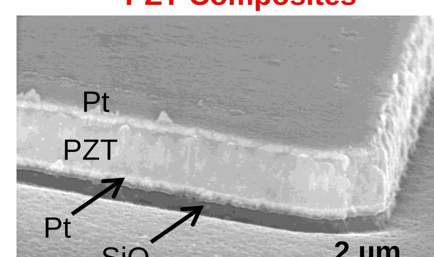


Polycrystalline Silicon





PZT Composites

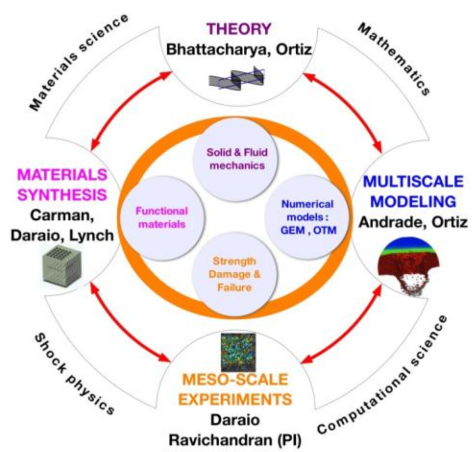


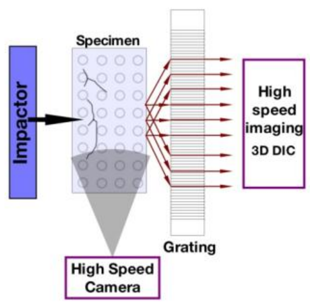
AFOSR/RW CO-SPONSORED COE'12 *(RW: Chhabildas)*

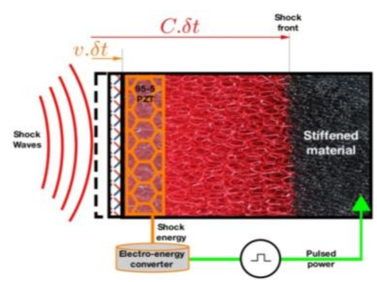
University Center of Excellence:
High-Rate Deformation Physics of Heterogeneous Materials
California Institute of Technology & University of California, Los Angeles

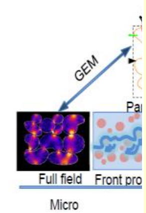
Goals:

- Develop a fundamental understanding of the deformation physics of heterogeneous materials at high-strain-rates and high-pressures
- Develop microstructures and functional nano-materials for mitigating shock and damage
- Use innovative methods for educating and training the next generation of scientists and practitioners









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Jimmy Xu (Brown U)
Erik Thostenson (U Del)^
Akira Todoroki (Tokyo Tech)
fu-Kuo Chang (Stanford U)*
*Xian Wang (Stanford U)**
*Boris Murmann (Stanford U)**
*Philip Levis (Stanford U)**
*Andrew Ng (Stanford U)**
*Robert McLeod (U CO)**
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*Yong Chen (UCLA)**
*Somnath Ghosh (Ohio St U)**
*Rahmat Shoureshi (NYIT)**
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*^ YIP; * MURI; + STTR*

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***Subject**:*	***PI's &** Co-PI's:*
Electromagnetically Tunable Fluids	***Gregory Huff (Texas A&M)***
Thermal Signature Reduction & EMI Shielding	***Jimmy Xu (Brown U)***
< Nanocomposites for Sensing & Actuation	***Erik Thostenson (U Del)^***
Damage Detection w Time Domain Reflectometry	***Akira Todoroki (Tokyo Tech)***
Bio-inspired Intelligent Sensing Materials	***fu-Kuo Chang (Stanford U)****
	*Xian Wang (Stanford U)**
	*Boris Murmann (Stanford U)**
	*Philip Levis (Stanford U)**
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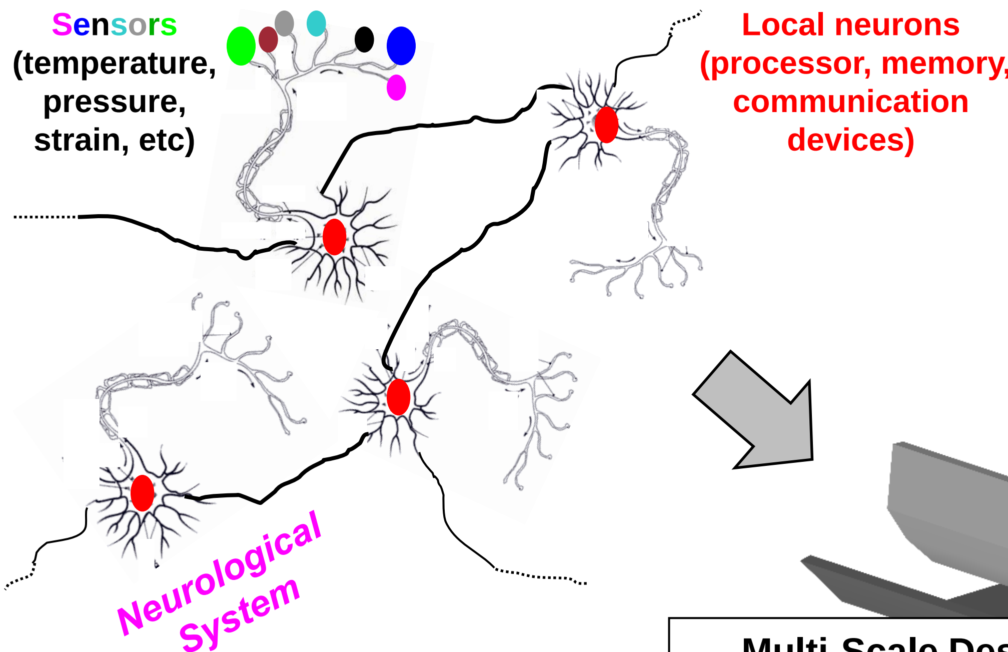
	*Somnath Ghosh (Ohio St U)**
	*Rahmat Shoureshi (NYIT)**
	*Frank Ko (U Brit Columbia)**
Embedded Sensors & Actuators for MAV	***Jeff Baur (AFRL/RXBC)***
"	***Ben Dickinson (AFRL/RWGN)***
"	***Greg Reich (AFRL/RBSA)***
> Load-Bearing Antennas of Conductive Textiles	***Yakup Bayram (PaneraTech)+***
"	***Rob Bortolin (NextGen)+***
"	***Francesca Scire (Phys Sci)+***

> New**; **< Concluded

^ YIP**; *** MURI**; **+ STTR

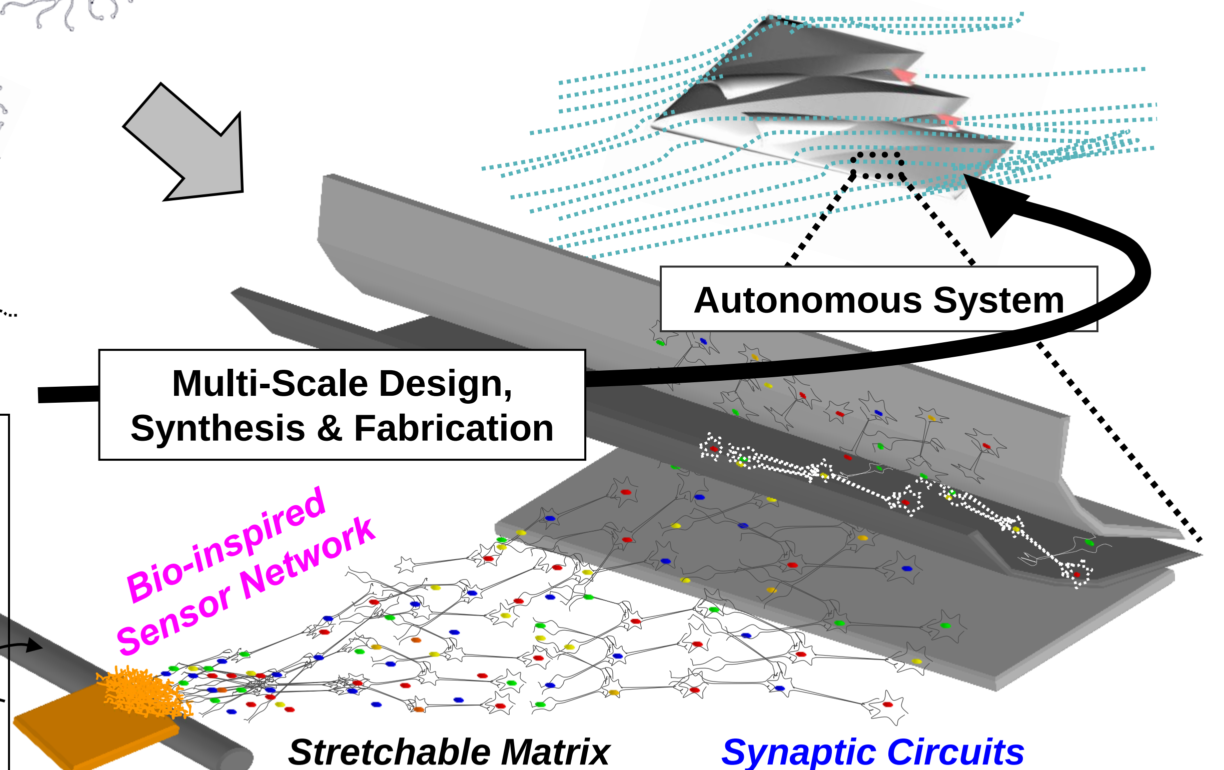
MURI '09

BUILT-IN SENSING NETWORK
(Stanford/U CO/UCLA/NYIT: Chang)



Synapse:

Cognition and decision-making are determined by a relative level of cumulative signal strength with respect to the synapse threshold values



Biological sensory systems rely on large numbers of sensors distributed over large areas and are specialized to detect and process a large number of stimuli. These systems are also capable to self-organize and are damage tolerant.

Sensor Network for Structural Integration

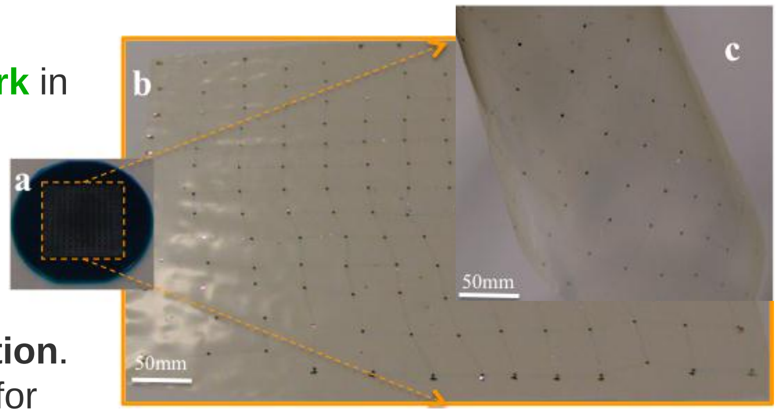
Task 1: Sensor Network for Structural Integration

To develop a nano/micro-scaled sensor network, functionalize the network to a macro scale, and integrate the sensor network into composite materials.

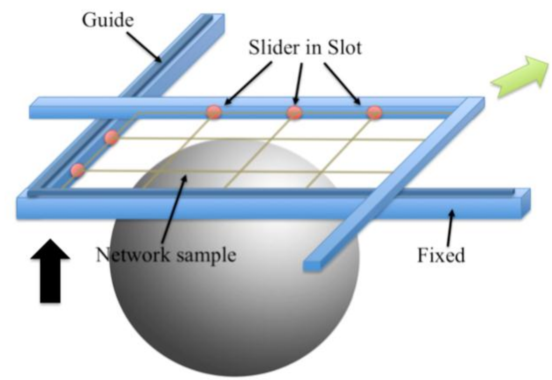
Chang’s group

To develop **PZT sensor network** in a CMOS-like foundry:

- Scaled down sensor network to **reduce wire & node size** (for higher spatial resolution).
- Developed spin-coated-on process for **network fabrication**.
- Developed a design method for **network expansion**.



13 by 13 stretchable temperature sensor network

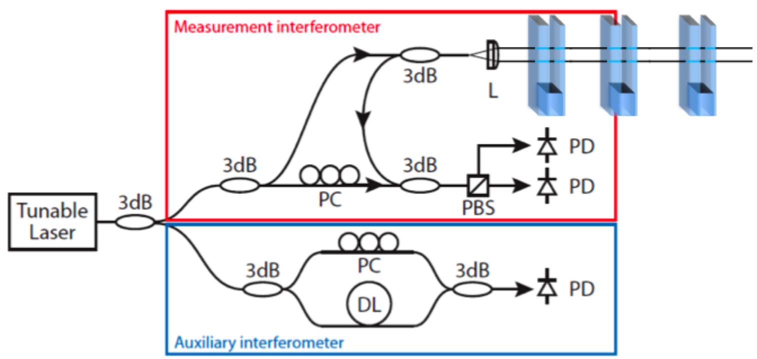


Conceptual design of test bed

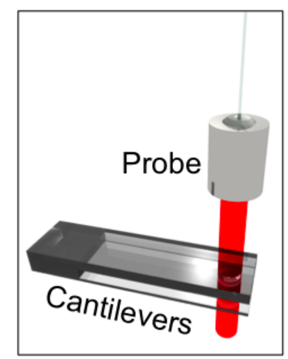
McLeod’s group

To develop ultra-precise **polymer optical sensor network** via **liquid deposition photolithography**:

- Deposition of polymer from the liquid state enables tightly integrated optical sensors.
- Atomic-scale precision: **0.53 nm**
- Interrogates thousands of sensors through **round-trip delay** to each partially-reflecting surface.



Precision Optical Frequency Domain Reflectometry



Self-referenced transducer

MURI ‘09

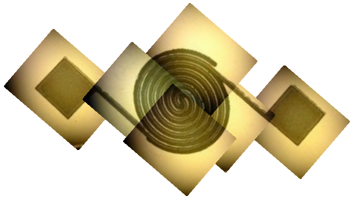
Micro/Nano Sensors for State Awareness

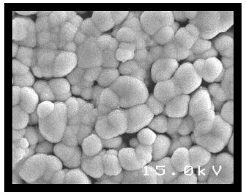
Task 2: Micro/Nano Sensors for State Awareness

To develop multi-physics multi-scale sensors for state awareness with an ease of network integration.

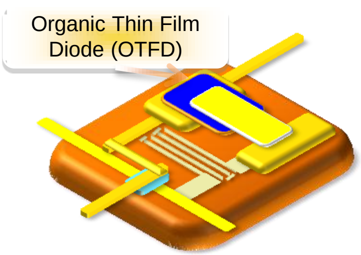
Chang’s group:

- Screen-printing **PZT sensors** onto a network
- Integrated **organic thin film diodes** into sensor network



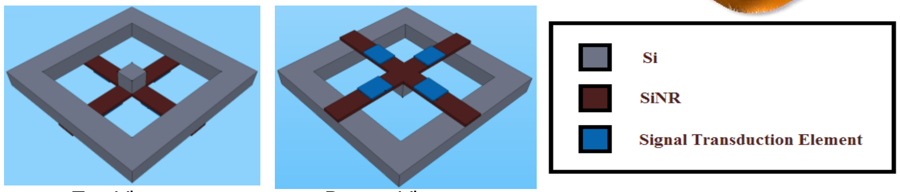


SEM image of good screen printed PZT



Wang’s group:

- Designed an **air flow sensor** measuring the direction and the velocity.
- Used four anisotropic **magnetostrictive s**tructures to transduce an air flow-induced beam deflection into a resistance change.

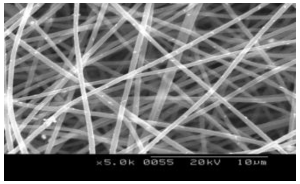


Top View

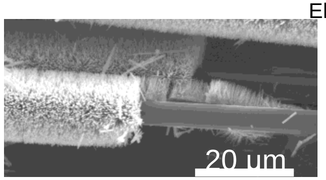
Bottom View

Ko’s group:

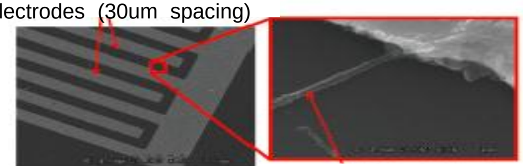
- Developed multi-functional **nanofibers** that can serve as: **magnetic**, **piezo-electric** and **chemical sensors**



Magnetic nanofibers



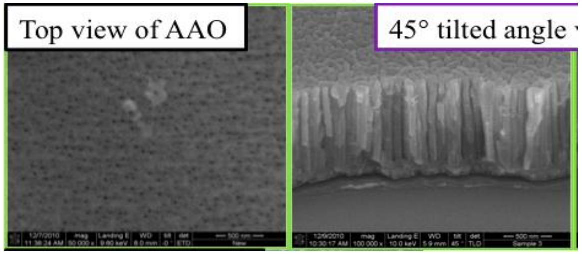
Piezoelectric fibers

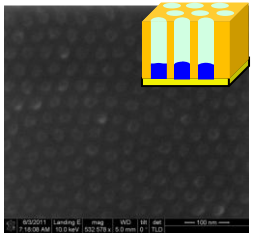


Nanofiber-based chemical sensors

Carman’s group:

- Investigated nano-structured **magneto-electric** materials for detecting **magnetic fields**.
- 40 and 25 nm diameter Ni nanostructures fabricated using AAO and DBC nanotemplate respectively.





DBC Polymer template

McLeod’s group:

- A new approach to **optical sensor** interrogation.

AFRL

Bio-inspired Neuron Circuits & Interface Electronics

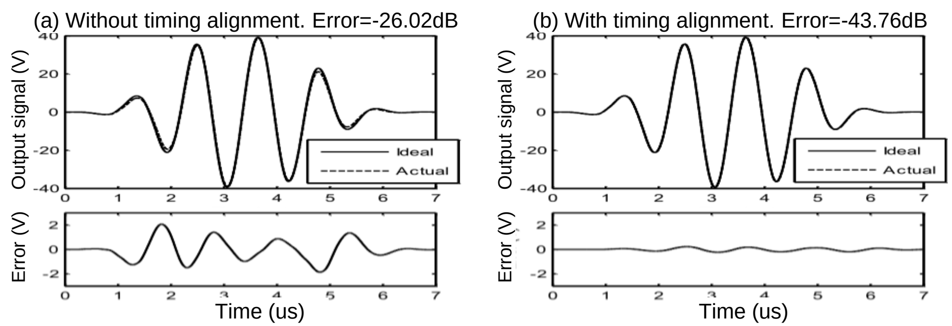
MURI '09

Task 3: Bio-inspired Neuron Circuits and Interface Electronics

To develop bio-inspired neuron circuits with appropriate electronics to interface with various sensors.

Murmann's group

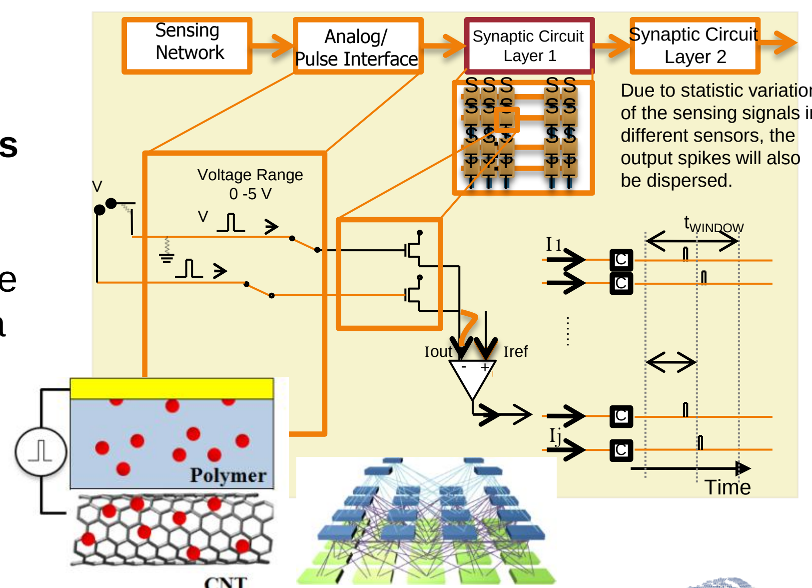
- Built a dense **integrated interface circuit** for ultrasonic sensing of the structural state.
- Defined **piezo driver** test chip to deliver a high voltage, high freq, continuous-time waveform.
- Plans to integrate piezo sensing interface with piezo driver on a **single chip**.



Output signals of the piezo-element driver without (left) and with (right) timing alignment

Chen's group

- Invented **synaptic transistors** with dynamic logic, memory, and learning functions by integrating ions in CNT/polymer composites.
- Voltage pulses can induce the **electrochemical reactions between ions and CNTs**, modifying the conductivities of CNTs reversibly for learning and memory functions.
- A **neuron circuit** with a large number of **synapses** can be fabricated by integrating an analog Si-CMOS circuit and a randomly connected CNT network in polymer composite.
- Integrated the first time the **synaptic transistors** with a **stretchable network** (from *Chang's group*) to process signals from an array of **temperature sensors**.
- Demonstrated that the integrated circuits can process the **temperature profile** dynamically.



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Scott White (UIUC)
Jeffrey Moore (UIUC)
Nicolaus Correll (U CO)
Scott White (UIUC)*
*Jeffrey Moore (UIUC)**
*Nancy Sottos (UIUC)**
*Jennifer Lewis (UIUC)**
*Philippe Geubelle (UIUC)**
*Kenneth Christensen (UIUC)**
*Jonathan Freund (UIUC)**
Jeff Baur (AFRL/RXBC)
Tom Darlington (Nanocomposix)+
Tony Starr (SensorMetrix)+

*** MURI; + STTR**

2012 AFOSR SPRING REVIEW

NAME: B. L

BRIEF DES
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Energy Ma
Actuation
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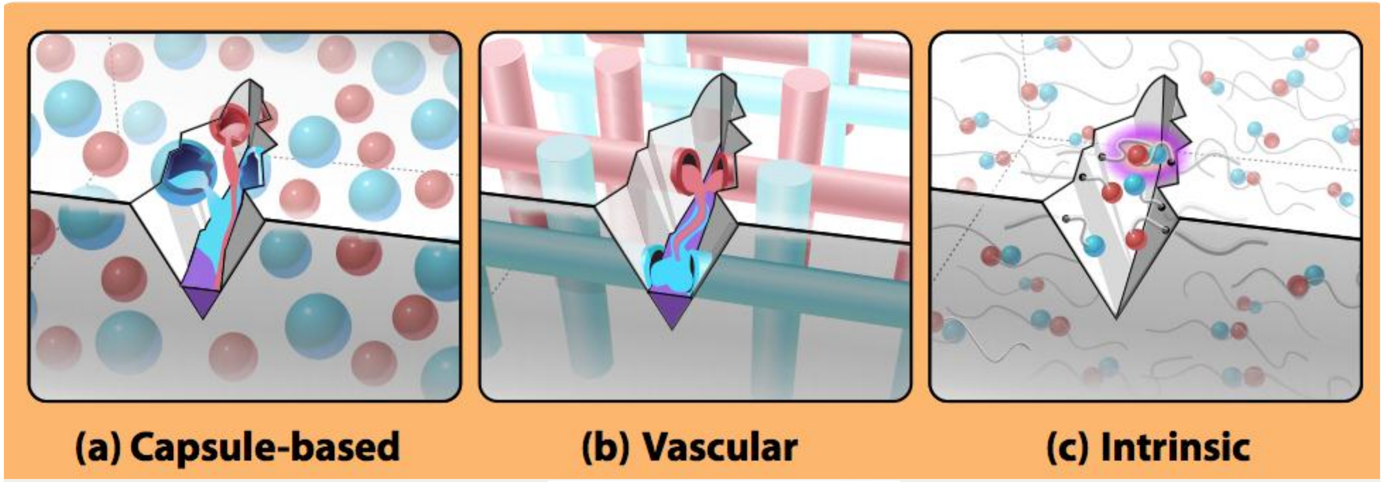
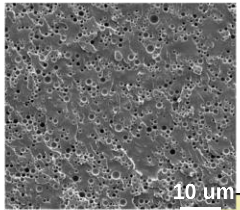
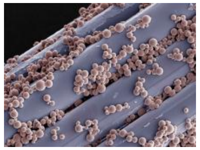
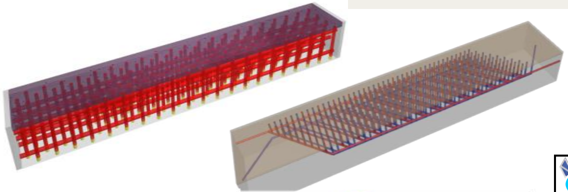
Subject:	***PI's &*** *Co-PI's:*
< Thermally Remendable Composites	***Sia Nemat-Nasser (UC San Diego)***
Interfacial Self-Healing in Composites	***Nancy Sottos (UIUC)***
Regeneration & Remodeling of Composites	***Scott White (UIUC)***
	Jeffrey Moore (UIUC)
> Self-Assembly and Self-Repair of Structures	***Nicolaus Correll (U CO)***
< Microvascular Autonomic Composites	***Scott White (UIUC)****
	*Jeffrey Moore (UIUC)**
	*Nancy Sottos (UIUC)**
	*Jennifer Lewis (UIUC)**
	*Philippe Geubelle (UIUC)**
	*Kenneth Christensen (UIUC)**
	*Jonathan Freund (UIUC)**
< Processing of Microvascular Structures	***Jeff Baur (AFRL/RXBC)***
Remendable Composites w Resistive Heating	***Tom Darlington (Nanocomposix)+***
	Tony Starr (SensorMetrix)+
> New; < Concluded	**** MURI; + STTR***

THREE APPROACHES FOR SELF-HEALING

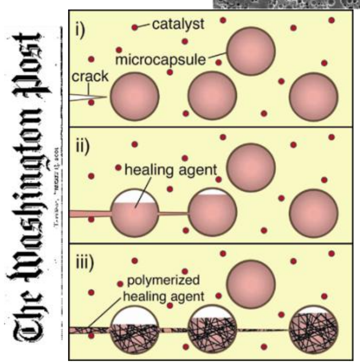


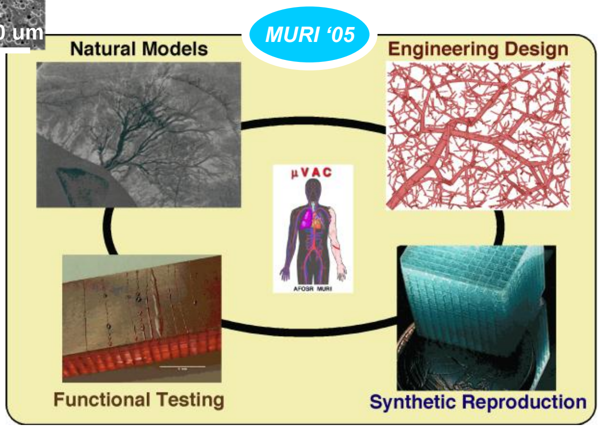


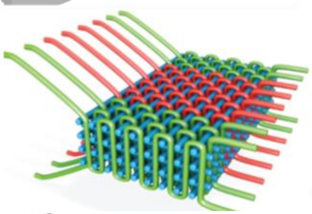


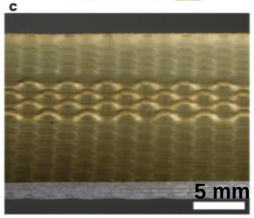


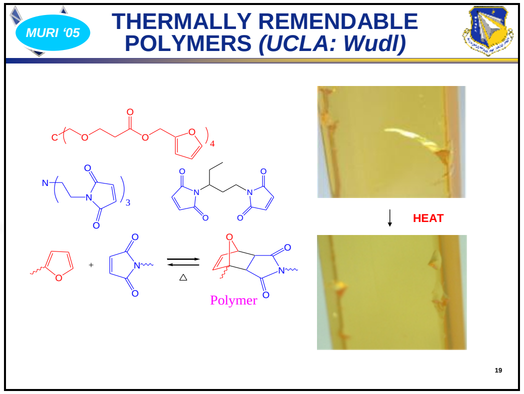
Nature











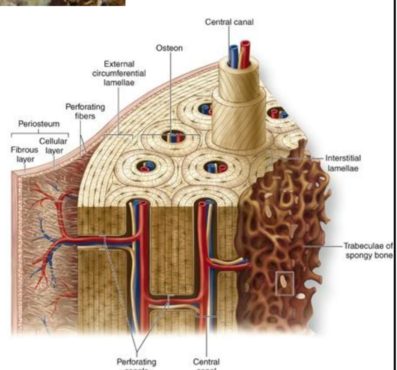
STRUCTURAL REGENERATION
(UIUC: White/Moore)

Regeneration and Remodeling in biology:

Tree skink lizard

Linckia starfish

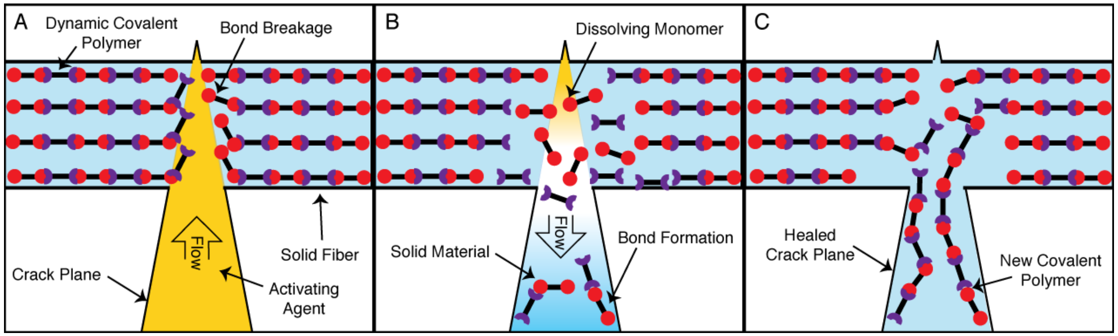
Human Bone



Conventional Material Systems:

- Passive materials not responsive to degradation
- Not adaptive to loading conditions
- Manual repair of damage
- Overdesign to account for reduction in mechanical properties and varied loading conditions

New approach: *Dynamic polymers + inert scaffolds*

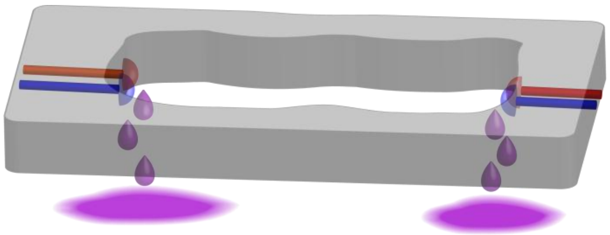


- Synthesized two types of **dynamic covalent bond based polymer** systems which can be **reversibly changed from liquid to solid and vice versa**
- **Poly(vinyl alcohol)** and **borate ions** undergo multiple **sol-gel** transitions under controlled pH
- **Reversible gel formation** of a functionalized poly(ethylene glycol) and crosslinker

STRUCTURAL REGENERATION: *Large Volume Damage*

Background:

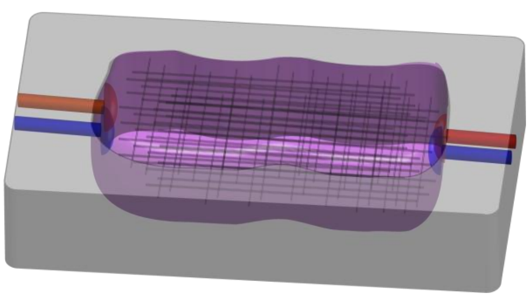
- Repair volume is limited by surface tension



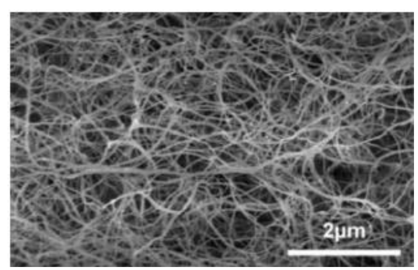
- **Self-assembled scaffolds** will provide temporary support as healing agents delivered

Progress:

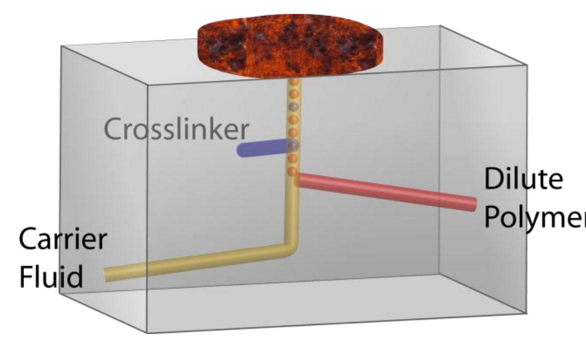
- **Sol-Gel transition** allowed three orders of magnitude stiffness increase
- Scaffold formation based on **peptide amphiphile hydrogels** is repeatable for multiple cycles
- Aggregate scaffolds formed by **hydrogen, covalent or ionic bonds** in progress
- Isolated constituents delivered via **vascular network**



Scaffold-supported damage region



Peptide Amphiphile Self-assembling Fibers



NAME: ***B. L. ("Les") Lee***

BRIEF DESCRIPTION OF PORTFOLIO:

Basic science for integration of emerging materi
into future Air Force systems requiring multi-fur

LIST OF SUB-AREAS:

Fundamentals of Mechanics of Materials;
Life Prediction (Materials & Micro-devices);
Sensing, Detection & Diagnosis;
Multifunctional Design of Autonomic Systems;
Multifunctional Design of Reconfigurable Syster
Self-Healing & Remediation;
Self-Cooling & Thermal Management;
Energy Management for Self-Sustaining System
Actuation & Threat Neutralization;
Engineered Nanomaterials

PI's *& Co-PI's:*

Abraham Stroock (Cornell U)
Noel Holbrook (Harvard U)
Vikas Prakash (Case Western)
Patrick Kwon (Mich St U)
George Lesieutre (Penn St U)
Aaron Esser-Kahn (UC Irvine)^
Scott White (UIUC)*
*Jeffrey Moore (UIUC)**
*Nancy Sottos (UIUC)**
*Jennifer Lewis (UIUC)**
*Philippe Geubelle (UIUC)**
*Kenneth Christensen (UIUC)**
*Jonathan Freund (UIUC)**
Ajit Roy (AFRL/RXBT)

^ YIP; * MURI

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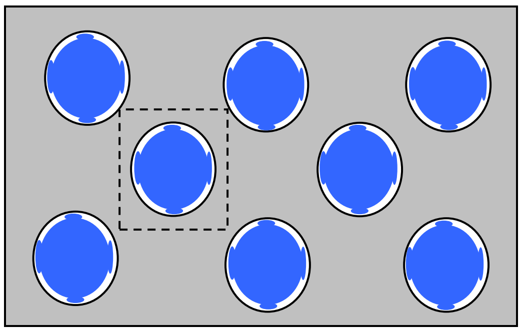
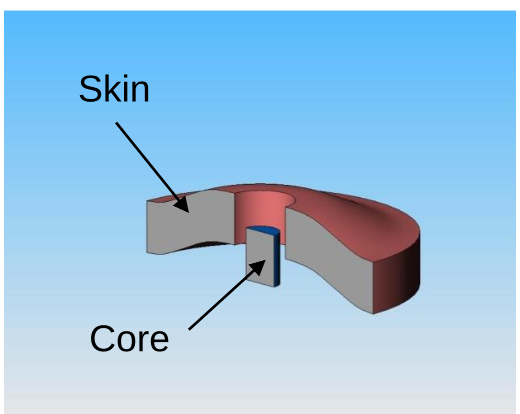
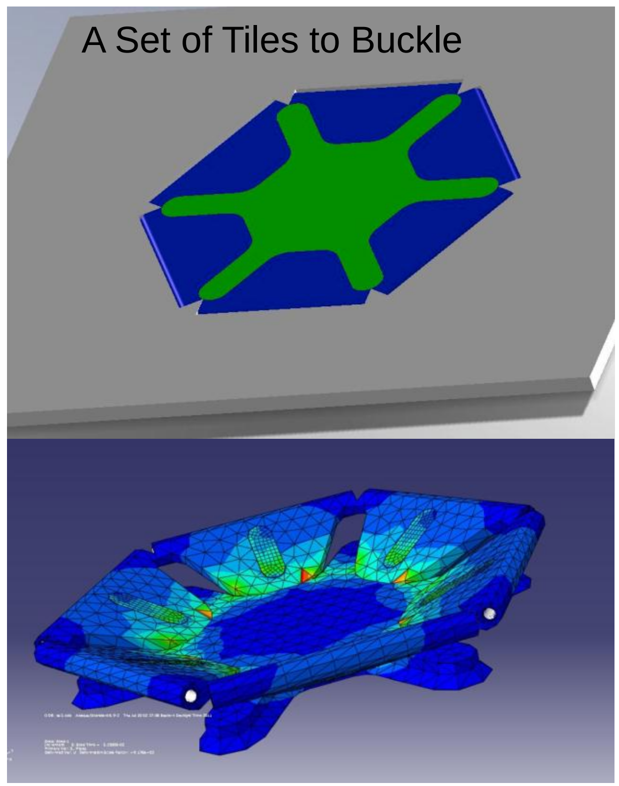
Subject:	***PI's*** *& Co-PI's:*
Plant-mimetic Heat Pipes	***Abraham Stroock (Cornell U)***
	Noel Holbrook (Harvard U)
< *CNT Based Thermal Interface Materials*	***Vikas Prakash (Case Western)***
New Generation of Perspirable Skin	***Patrick Kwon (Mich St U)***
Variable Thermal Conductivity Structures	***George Lesieutre (Penn St U)***
> *Microvascular Systems for Mass/Energy Transport*	***Aaron Esser-Kahn (UC Irvine)^***
< *Microvascular Autonomic Composites*	***Scott White (UIUC)****
	*Jeffrey Moore (UIUC)**
	*Nancy Sottos (UIUC)**
	*Jennifer Lewis (UIUC)**
	*Philippe Geubelle (UIUC)**
	*Kenneth Christensen (UIUC)**
	*Jonathan Freund (UIUC)**
Carbon Fiber Morphology for Thermal Materials	***Ajit Roy (AFRL/RXBT)***
> *New*; < *Concluded*	**^ *YIP*; * *MURI***

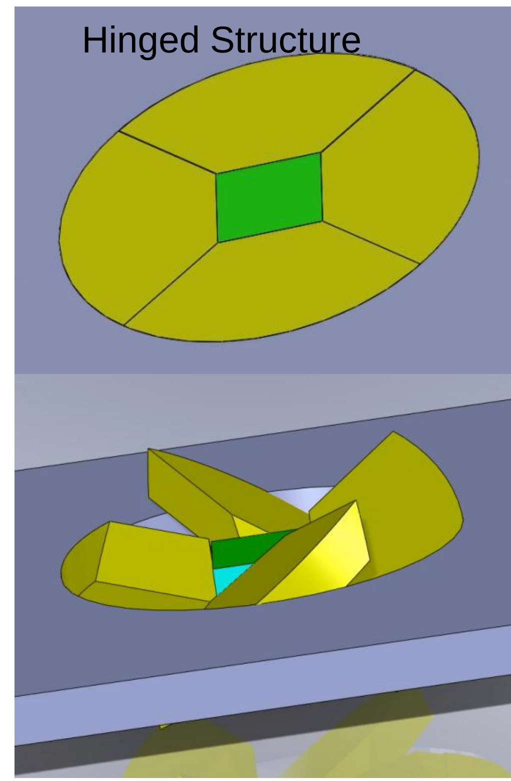
PERSPIRABLE SKIN OF CERAMICS *(Mich State U: Kwon)*

- **Approach (I): Deformable materials under thermal loading** (The interference between two distinct materials that has been shrink-fitted opens for cooling; gap is not large enough)
- **Approach (II): A set of tiles to buckle under thermal loading** (Upon heating, the tiles push on the core radially, while shrinking circumferentially, enabling a buckling action)
- **Approach (III): A hinged structure triggered by internal pressure** (The assembly consists of the skin (rectangular part), two half circular tiles, and two axes to provide a rotation)





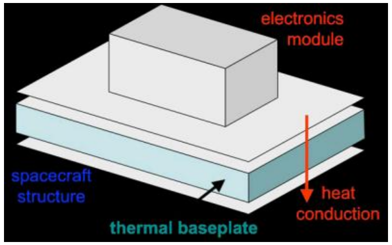




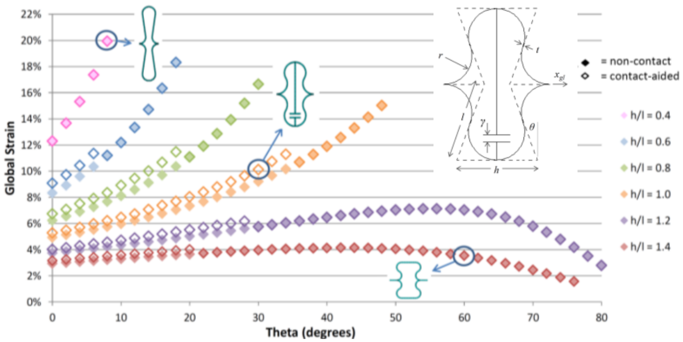
THERMAL BASE PLATE DESIGN
(Penn State: Lesieutre)

Need for Material Systems with Variable Thermal Conductivity

- **Electronic modules** are designed to operate near room temperature and they generate significant heat loads. They are connected to the spacecraft bus structure via a **thermal base plate** which is intrinsically **multifunctional**.
- The thermal base plate transfers **mechanical load** and transfers **heat** away from (or insulates) the electronics module in order to ensure that the electronics do not overheat (or become too cold).



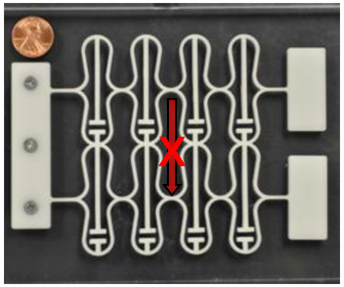
- Active and passive **thermal switches** exist, and passive ones are preferred for low power and complexity.



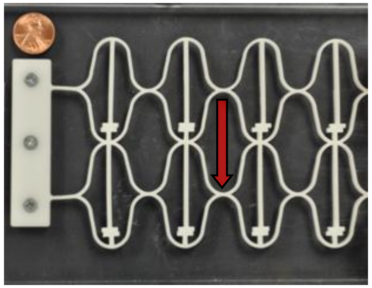
Global strain vs. Cell angle parameter

Cellular Contact-aided Compliant Mechanisms (C3M):

- C3M allow the design of **cellular structures with novel integrated contact mechanisms** that provide **local stress relief** under high loads. They are capable of ultimate strains exceeding 10%, while bulk ceramic materials have high strength, but low strain at failure (0.2-1%).
- Using **multiple materials** (e.g. **ceramic-metal** combination), these contacts also introduce new thermal conduction pathways and provide a novel potential avenue to **passive thermal switches**.
- When the "hot side" of the thermal base plate is **below a threshold temperature**, the base plate is in a **thermally-insulating** state, associated mainly with ceramic parts of the C3M based structure.
- As the temperature of the "hot side" increases **above threshold value**, the C3M based structure expands and **internal contact** is made between conducting members, dramatically **increasing the thermal conductivity** of the base plate. This conductivity is maintained at higher temperatures.

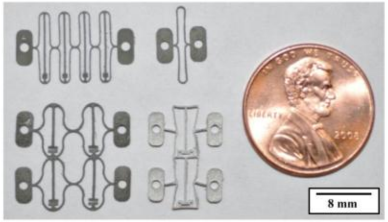


Non-Conducting



Conducting

metal/ceramic parts made by "lost mold, rapid infiltration forming" (LM-RIF) process



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Self-Cooling & Thermal Management;
Energy Management for Self-Sustaining Systen
Actuation & Threat Neutralization;
Engineered Nanomaterials

***PI's** & Co-PI's:*

Max Shtein (U Mich) #
Henry Sodano (U FL)
Dan Inman (VA Tech)
Sven Bilén (Penn St U)
Michael Strano (MIT)
Greg Carman (UCLA)
Wonbong Choi (FL Int'l U)
Hugh Bruck (U MD)
Gleb Yushin (GA Tech)^
Minoru Taya (U WA)*
*Paolo Feraboli (U WA)**
*Martin Dunn (U CO)**
*Kurt Maute (U CO)**
*Se-Hee Lee (U CO)**
*Tom Hahn (UCLA)**
*Dan Inman (VA Tech)**
*Ioannis Chasiotis (UIUC)**
Michael Durstock (AFRL/RXBN)
Benji Maruyama (AFRL/RXBN)
John Coggin (Prime Photonics)+
Nersesse Nersessian (MAPCo)+
Anuncia Gonzalez (Lynntech)+

*# PECASE; ^ YIP; * MURI; + STTR*

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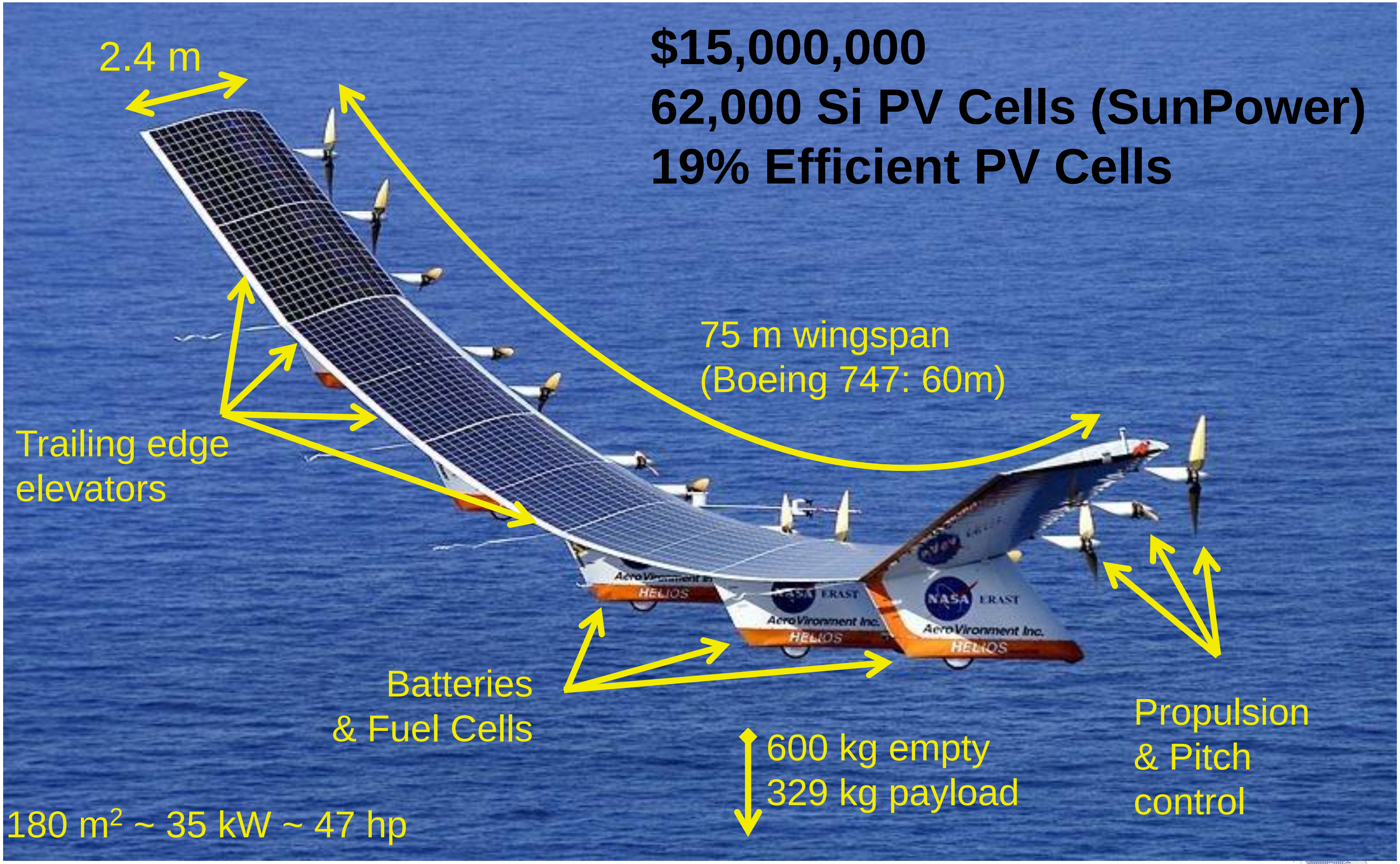
Subject:	***PI's** & Co-PI's:*
Energy Harvesting Textile Composites	***Max Shtein (U Mich)** #*
Active Structural Fibers for Multif'l Composites	***Henry Sodano (U FL)***
Vibration Suppression and Energy Harvesting	***Dan Inman (VA Tech)***
Energy Harvesting Using Electrodynamic Tethers	***Sven Bilén (Penn St U)***
Environmental Hydrocarbon Harvesting Via CNT	***Michael Strano (MIT)***
Nanoscale Based Thermal Energy Harvesting	***Greg Carman (UCLA)***
Flexible Battery of Graphene-CNT Hybrid	***Wonbong Choi (FL Int'l U)***
> Integrated Solar Cells for MAV Wings	***Hugh Bruck (U MD)***
< Multifunctional Mg-Li Alloy Nanocomposites	***Gleb Yushin (GA Tech)^***
< Energy Harvesting/Storage System Integration	***Minoru Taya (U WA)****
	*Paolo Feraboli (U WA)**
	*Martin Dunn (U CO)**
	*Kurt Maute (U CO)**
	*Se-Hee Lee (U CO)**
	*Tom Hahn (UCLA)**
	*Dan Inman (VA Tech)**
	*Ioannis Chasiotis (UIUC)**
Nanomaterials for Structural Batteries	***Michael Durstock (AFRL/RXBN)***
	Benji Maruyama (AFRL/RXBN)
> Hybrid Energy Harvesting Systems	***John Coggin (Prime Photonics)+***
"	***Nersesse Nersessian (MAPCo)+***
"	***Anuncia Gonzalez (Lynntech)+***

> New; < Concluded

 # PECASE; ^ YIP; * MURI; + STTR

NASA "HELIOS"



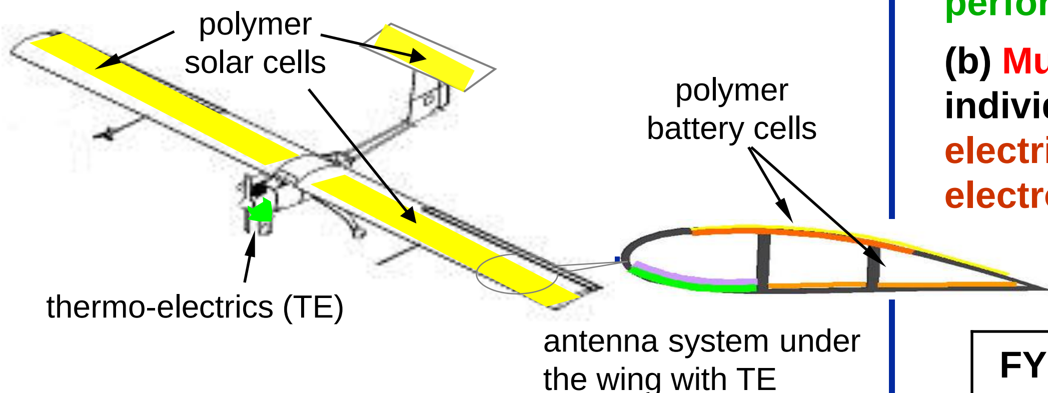
$15,000,000
62,000 Si PV Cells (SunPower)
19% Efficient PV Cells
2.4 m
75 m wingspan
(Boeing 747: 60m)
Trailing edge
elevators
Batteries
& Fuel Cells
600 kg empty
329 kg payload
Propulsion
& Pitch
control
180 m² ~ 35 kW ~ 47 hp

MURI '06

INTEGR'D ENERGY HARVESTING
(U WA/U CO/UCLA/VT: Taya)

Objective:

To develop "self-powered" load-bearing structures with integrated energy harvest/ storage capabilities, and to establish new multi-functional design rules for structural integration of energy conversion means.



DoD Benefit:

Self-powered load-bearing structures with integrated energy harvest/storage capabilities will provide meaningful mass savings and reduced external power requirements over a wide range of defense platforms including space vehicles, manned aircraft, unmanned aerial vehicles, and ISR systems.

Technical Approach:

(a) A combination of experimental and analytical techniques are employed to advance the efficiency of the energy conversion means (as an integral part of load-bearing structures) and to optimize their multifunctional performance and ability to cover larger areas.

(b) Multifunctional composites are created with individual layers acting as photovoltaic/thermo-electric/piezoelectric power harvesting and electrochemical power storage elements.

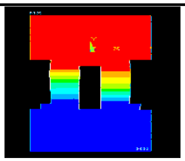
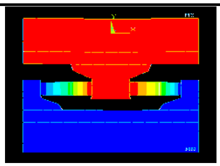
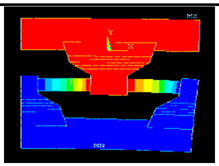
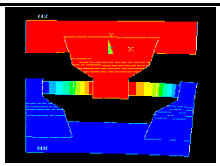
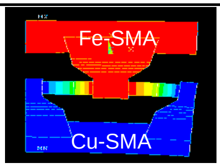
Budget:

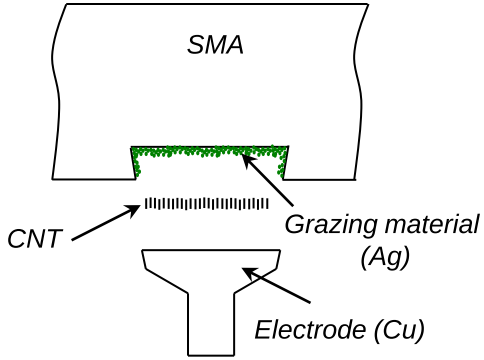
	FY06	FY07	FY08	FY09	FY10	FY11
$K	693,335	1,169,560	1,180,608	1,219,324	1,179,991	568,571

Major Reviews/Meetings:

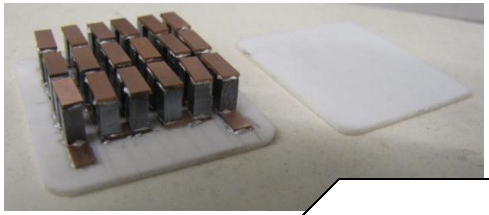
- 29 August 2007: Seattle, WA
- 5 August 2008: Boulder, CO
- 11 August 2009: Blacksburg, VA
- 18 August 2010: Los Angeles, CA
- 5 August 2011: Arlington, VA

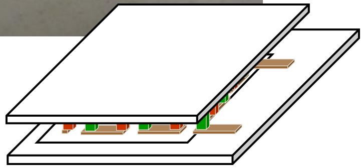
MURI '06 Thermoelectric Module Integration

TE design / Analysis results	Phi TE	Linear TE	Linear TE w/ FGM and shrink-fit (1.25mm)	Linear TE w/ FGM and shrink-fit (2.5mm)	Linear TE w/ FGM and shrink-fit (2.5mm)
					 450C 50C
Generated temperature gap across TE element (deg C)	338	344	344	346	394
Maximum normal stress on electrode (Mpa)	-1100	-1200	-535	-591	-642
Maximum shear stress on electrode (MPa)	146	617	329	311	337
Maximum shear stress on TE element (MPa)	125	71	34	43	56
Power density (W/cm2)	**0.80**	**0.87**	**0.87**	**0.89**	**1.15**
Module efficiency (%)	**12.8**	**13.3**	**13.3**	**13.4**	**14.8**



- **n-type: $Mg_2Si_{0.96}Bi_{0.03}In_{0.01}$**
- **p-type: $Si_{0.93}Ge_{0.05}B_{0.02}$**
- Heat source side: Fe-SMA
- Heat exhaust side: Cu-SMA
- CNT in grazing material gives:
  - ✓ locking Ag
  - ✓ reducing the creep strain

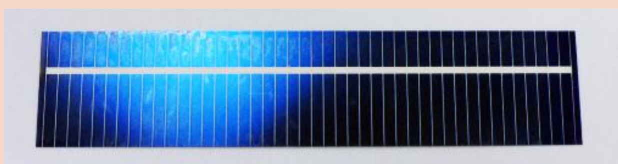




AFRL

MURI '06

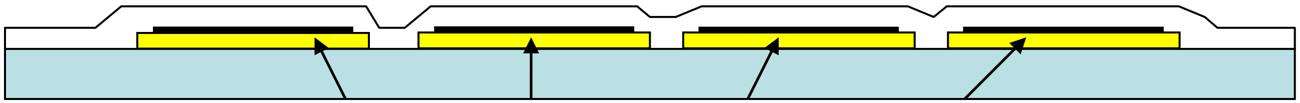
Comparison of Solar Cells for Structural Integration

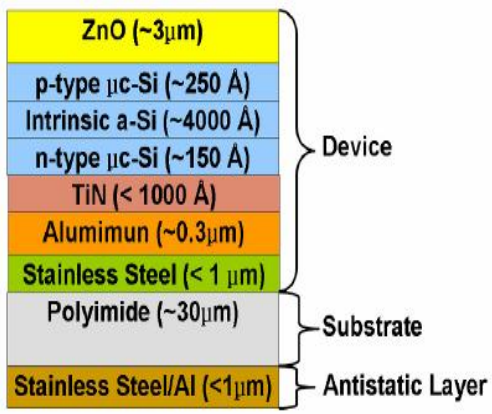
	Monocrystalline Silicon Solar Cell	Amorphous Silicon Solar Cell
Tensile Loading	Breaks at **0.23 %** tensile strain	Works well at **1.6 %** tensile strain. Composite laminates breaks around 1.5 % strain.
Fatigue Loading	N/A	Works well at fatigue cycle of 0.3 % strain
Efficiency	**23 %**	12 %
Price	High (200 um thick c-Si needed)	Low (about **1 um** thick a-Si needed)
Sample		

	Cu(In,Ga)Se_2 Solar Cell	Dye Sensitized Solar Cell
Pros	**Highest efficiency** among thin film solar cells	**Cheapest** among thin film solar cells
Cons	Degrades with **humidity**; manufacturing generates very toxic gases to the environment.	Unstable efficiency; extremely **corrosive**

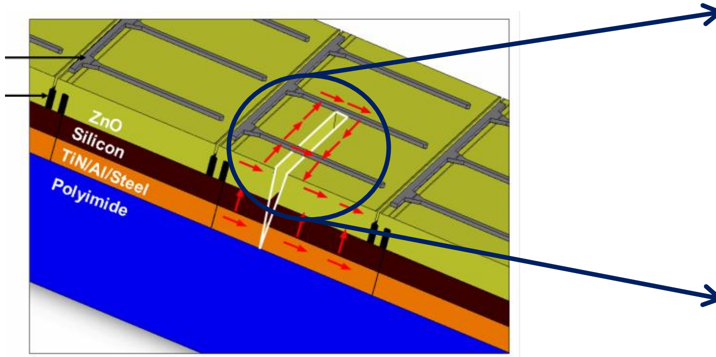
AFRL

Solar Cells Under Fatigue

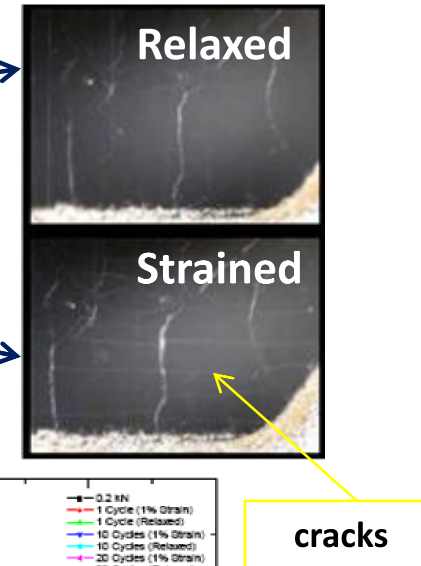


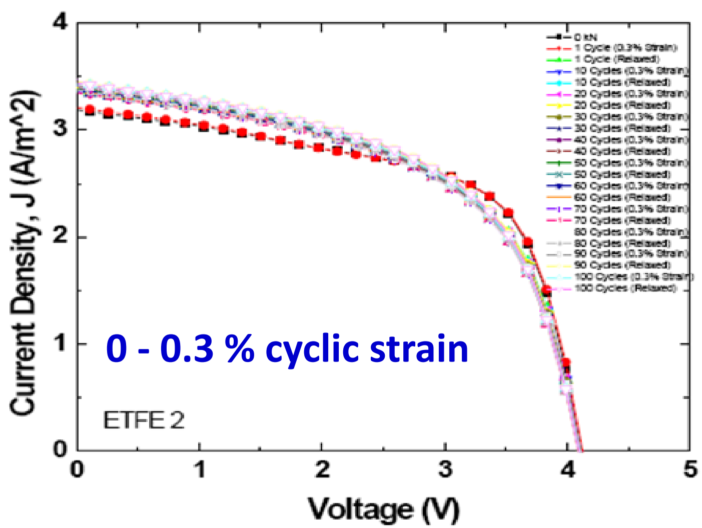


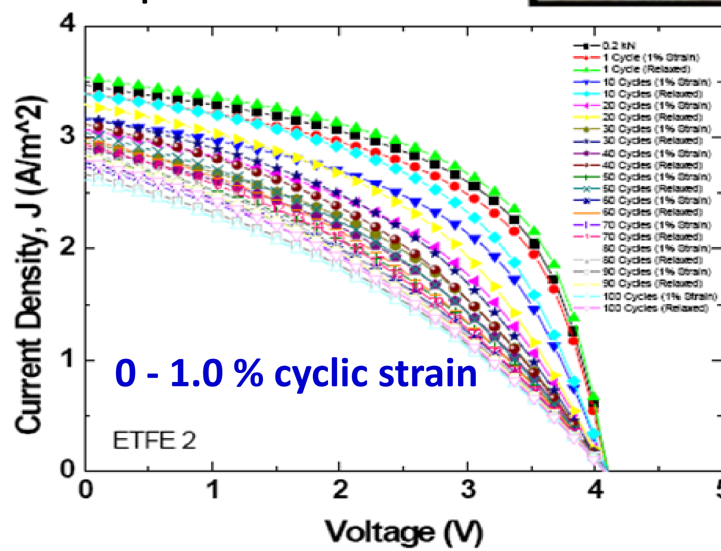
Free standing amorphous Si solar cells



current path

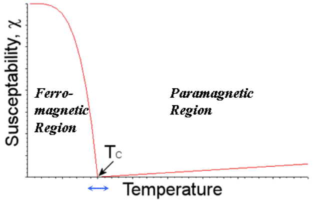


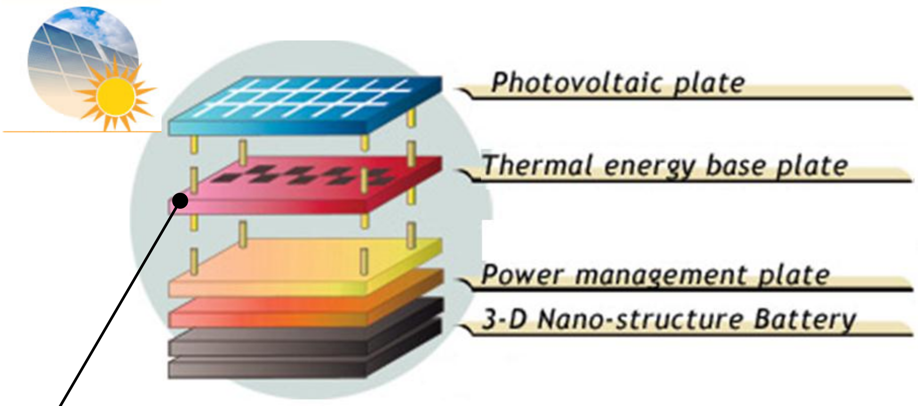


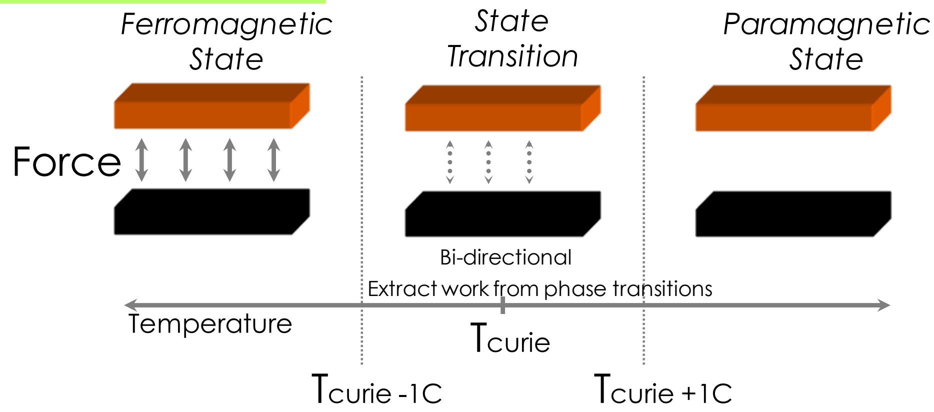


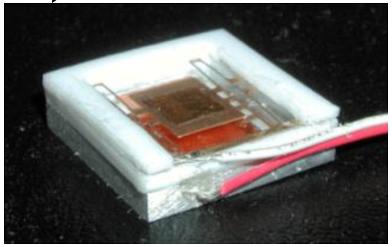
STTR' 10: HYBRID ENERGY HARVEST

- Pairing solar panels with magneto-thermoelectric power generator as "active thermal backplane" for solar panel cooling and "hybrid energy harvest"

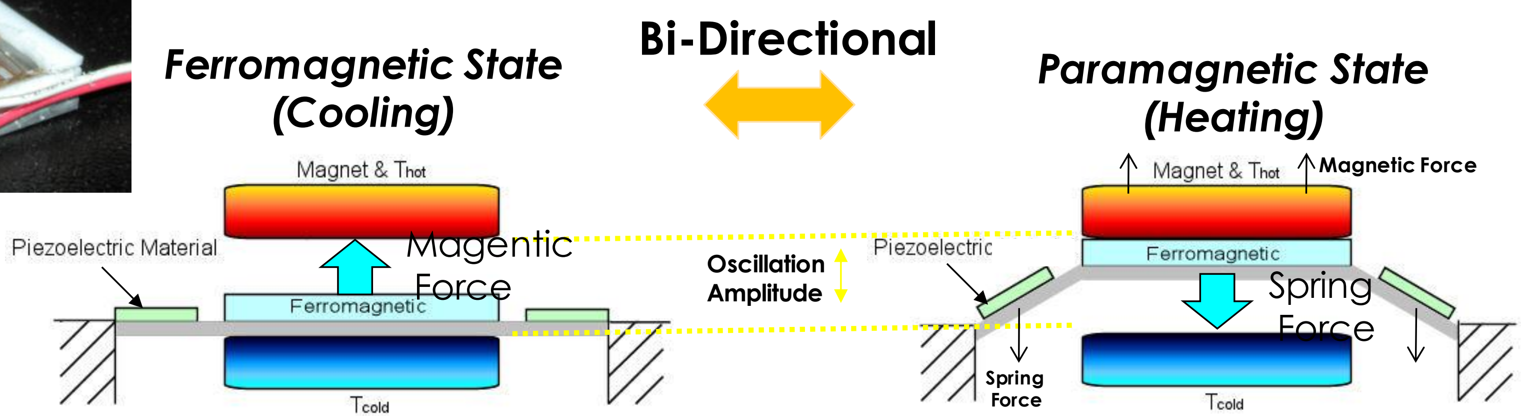








magneto-thermoelectric power generator *(STTR'07)*



2012 AFOSR SPRING REVIEW

NAME: ***B. L. ("Les") Lee***

BRIEF DESCRIPTION OF PORTFOLIO:

Basic science for integration of emerging mater
into future Air Force systems requiring multi-fur

LIST OF SUB-AREAS:

Fundamentals of Mechanics of Materials;
Life Prediction (Materials & Micro-devices);
Sensing, Detection & Diagnosis;
Multifunctional Design of Autonomic Systems;
Multifunctional Design of Reconfigurable Syster
Self-Healing & Remediation;
Self-Cooling & Thermal Management;
Energy Management for Self-Sustaining System
Actuation & Threat Neutralization;
Engineered Nanomaterials

PI's *& Co-PI's:*

Nicolas Triantafyllidis (U Mich)
John Shaw (U Mich)
Patrick Mather (Syracuse U)
H. Jerry Qi (U CO)
Martin Dunn (U CO)
Benjamin Shapiro (U MD)
Elisabeth Smela (U MD)
Shiv Joshi (NextGen)
Sharon Swartz (Brown U)
Nakhiah Goulbourne (VA Tech)
Minoru Taya (U WA)
Frank Ko (U Brit Columbia)
Aaron Dollar (Yale U)^
A. John Hart (U Mich)^
Xin Zhang (Boston U)
C. T. Sun (Purdue U)
Thomas Siegmund (Purdue U)
Anna Balazs (U Pitt)
Nicole Zacharia (Texas A&M)
Richard Vaia (AFRL/RXBN)
Greg Reich (AFRL/RBSA)

^ YIP

2012 AFOSR SPRING REVIEW

NAME: *B. L*

BRIEF DES

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Fundamen

Life Predic

Sensing, D

Multifuncti

Multifuncti

Self-Healin

Self-Coolin

Energy Ma

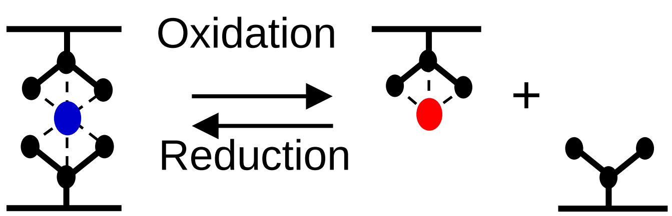
Actuation

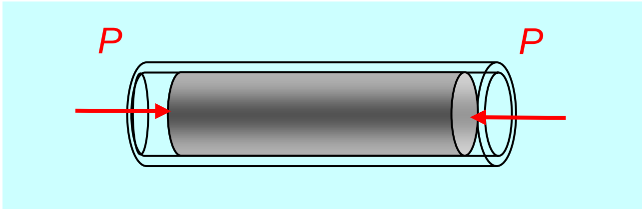
Engineere

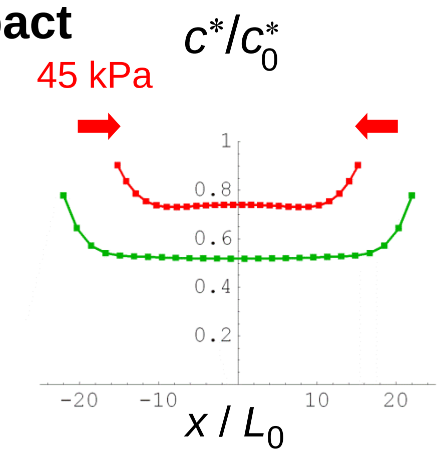
Subject:	***PI's** & Co-PI's:*
< *Cellular Shape Memory Structures*	***Nicolas Triantafyllidis (U Mich)*** *John Shaw (U Mich)*
< *Reversible Shape Memory Polymer Composites*	***Patrick Mather (Syracuse U)*** *H. Jerry Qi (U CO)* *Martin Dunn (U CO)*
< *Electroosmotically Actuated Shape Change*	***Benjamin Shapiro (U MD)*** *Elisabeth Smela (U MD)*
Ultra-Maneuverable Bat Technologies	***Shiv Joshi (NextGen)*** *Sharon Swartz (Brown U)* *Nakhiah Goulbourne (VA Tech)*
Bio-inspired Design of Reconfigurable Structures	***Minoru Taya (U WA)*** *Frank Ko (U Brit Columbia)*
Active Cells for Multifunctional Structures	***Aaron Dollar (Yale U)^***
Morphing CNT Microstructures	***A. John Hart (U Mich)^***
Metamaterial Enhanced MEMS	***Xin Zhang (Boston U)***
Acoustic Metamaterials w Local Resonance	***C. T. Sun (Purdue U)***
Macroscale Meta-Materials	***Thomas Siegmund (Purdue U)***
Active Materials w Sensory & Adaptive Capabilities	***Anna Balazs (U Pitt)***
> *Mechano-Responsive Polymer Systems*	***Nicole Zacharia (Texas A&M)***
Mechanically-Responsive Polymers	***Richard Vaia (AFRL/RXBN)***
Thermally-Activated Reconfigurable Systems	***Greg Reich (AFRL/RBSA)***
> *New*; < *Concluded*	***^ YIP***

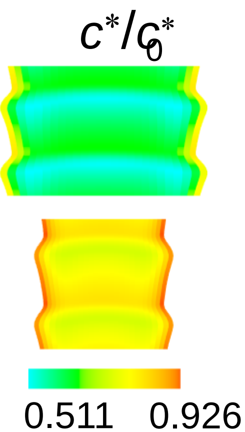
DESIGNING SELF-REINFORCING MATERIALS *(U Pitt: Balazs)*

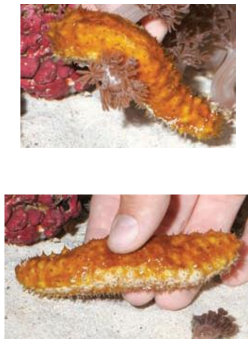
- **Developed model to describe BZ gels with chemo-responsive X-links**
  - **Modified Oregonator model**
  - ***f* – dependent complex formation**
  - **Time-dependent elastic contribution**
- **Studied response to steady and periodic compression in 1D model**
- **Mechanical impact increases X-link density**
  - **Self-reinforcing material**
  - **Stiffens in response to impact**





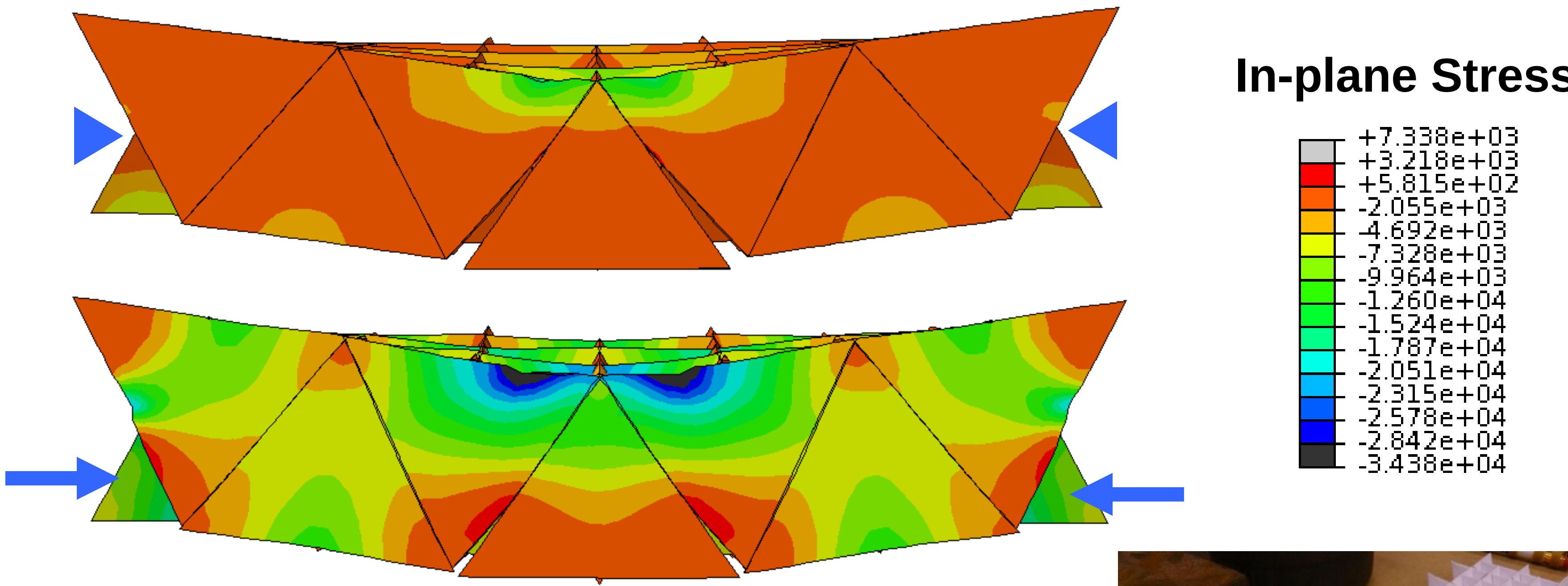


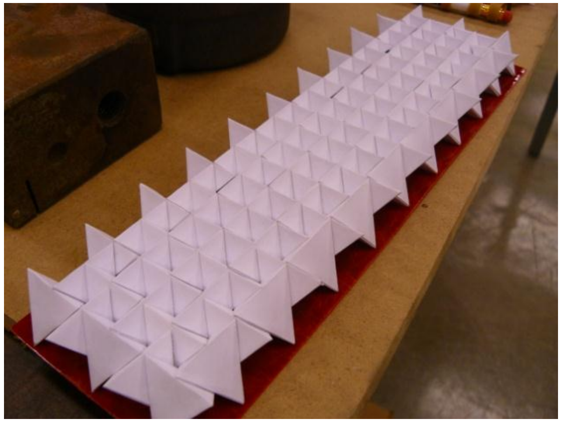




V.V. Yashin, O. Kuksenok, A.C. Balazs, *J. Phys. Chem. B* 2010, 114(19), 6316.

TOPOLOGICAL INTERLOCKING
(Purdue U: Siegmund)





- **Confinement changes translate in change on contact conditions**
- **Large confinement leads to smaller opening and more resistance to load**
- **Retain damage tolerance in the high stiffness regime**

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Erik Thostenson (U Del)^
*Frank Ko (U Brit Columbia)**
Jeff Baur (AFRL/RXBC)
Nancy Sottos (UIUC)
Vikas Prakash (Case Western)
Ajit Roy (AFRL/RXBT)
Michael Strano (MIT)
Greg Carman (UCLA)
Wonbong Choi (FL Int'l U)
Gleb Yushin (GA Tech)^
*Se-Hee Lee (U CO)**
Michael Durstock (AFRL/RXBN)
A. John Hart (U Mich)
Richard Vaia (AFRL/RXBN)
Ray Baughman (U Texas Dallas)
Nicholas Kotov (U Mich)
Mrinal Saha (OK St U)
Tsu-Wei Chou (U Del)
Yuntian Zhu (NCSU)
Alexander Bogdanovich (NCSU)
Philip Bradford (NCSU)

^ YIP; * MURI

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***Subject*:**	***PI's* *& Co-PI's:***
Thermal Signature Reduction & EMI Shielding	***Jimmy Xu (Brown U)***
Nanocomposites for Sensing & Actuation	***Erik Thostenson (U Del)^***
Bio-inspired Intelligent Sensing Materials	*Frank Ko (U Brit Columbia)**
Embedded Sensors & Actuators for MAV	***Jeff Baur (AFRL/RXBC)***
Interfacial Self-Healing in Composites	***Nancy Sottos (UIUC)***
CNT Based Thermal Interface Materials	***Vikas Prakash (Case Western)***
Carbon Fiber Morphology for Thermal Materials	***Ajit Roy (AFRL/RXBT)***
Environmental Hydrocarbon Harvesting Via CNT	***Michael Strano (MIT)***
Nanoscale Based Thermal Energy Harvesting	***Greg Carman (UCLA)***
Flexible Battery of Graphene-CNT Hybrid	***Wonbong Choi (FL Int'l U)***
Multifunctional Mg-Li Alloy Nanocomposites	***Gleb Yushin (GA Tech)^***
Energy Harvesting/Storage System Integration	*Se-Hee Lee (U CO)**
Nanomaterials for Structural Batteries	***Michael Durstock (AFRL/RXBN)***
Morphing CNT Microstructures	***A. John Hart (U Mich)***
Mechanically-Responsive Polymers	***Richard Vaia (AFRL/RXBN)***
Artificial Muscles for Large Stroke & High Force	***Ray Baughman (U Texas Dallas)***
< Layer-by-layer Processing of CNT Composites	***Nicholas Kotov (U Mich)***
< Hierarchical Structures of CNT Composites	***Mrinal Saha (OK St U)***
Thin Flexible CNT Composites	***Tsu-Wei Chou (U Del)*** *Yuntian Zhu (NCSU)*
> Shear Pressed CNT Sheets for Strain Sensing	***Alexander Bogdanovich (NCSU)*** *Philip Bradford (NCSU)*
***> New*; < Concluded**	***^ YIP; * MURI***

CNT YARNS FOR ARTIFICIAL MUSCLES *(UT Dallas: Baughman)*

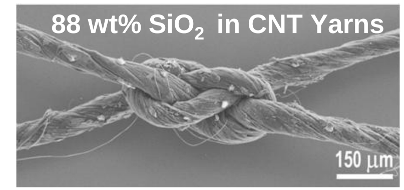
"Biscrolling Nanotube Sheets and Functional Guests into Yarns", Science 331, 51 (2011).

- **Weavable, sewable, braidable** and **knottable** carbon nanotube (CNT) **yarns** that can contain over 92 wt% of **functional guest powders** are made by twist insertion in a guest/CNT sheet stack.
- Demonstrated use of these **"biscrolled" yarns** as **battery/fuel cell electrodes** and as **superconductors**.

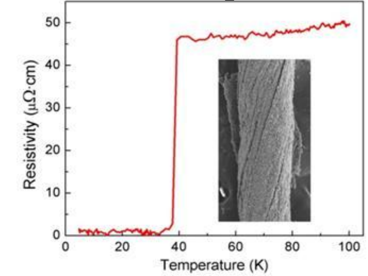
"Torsional Carbon Nanotube Artificial Muscles", Science 334, 494 (2011).

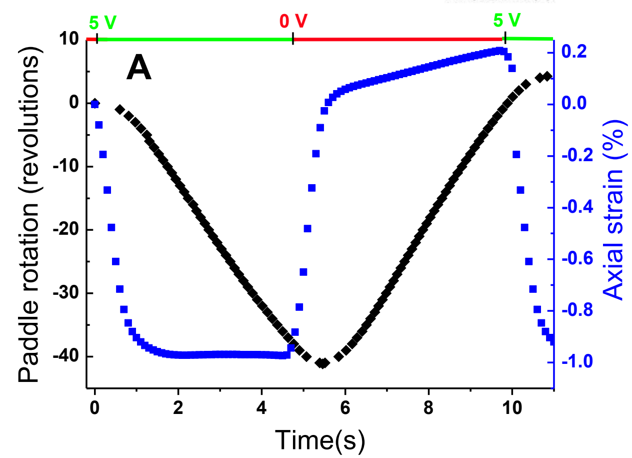
- **Tensile** and **torsional actuation** results from **yarn volume change** caused by **ion influx** to compensate **electronically injected charge**. Torsional rotation per actuator length was 1000 times that of prior-art torsional actuators.
- The actuating yarn electrode can accelerate an 1800 times heavier paddle up to 590 revolutions/min in 1.2 s and provide similar gravimetric torque and mechanical power generation per yarn weight as for large electric motors. **Microfluidic** application was demonstrated.

Biscrolling process



Superconducting MgB_2/CNT yarn





Torsional and tensile actuation for electrochemically driven twist-spun yarns

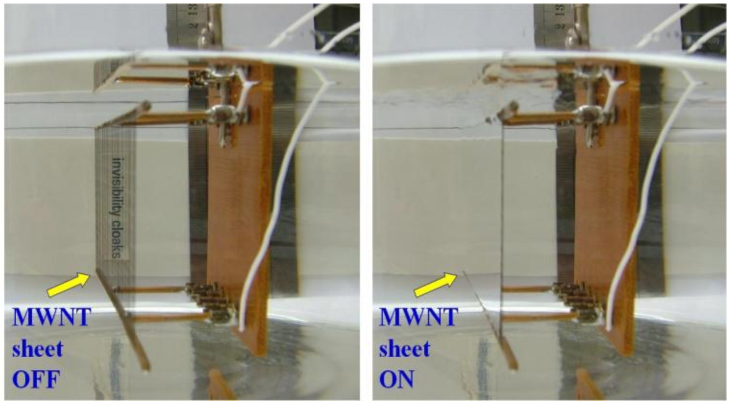
MIRAGE EFFECT OF CNT SHEET
(UT Dallas: Baughman)

"Mirage Effect from Thermally-modulated Transparent Carbon Nanotube Sheet", Nanotechnology ***22****, 435704 (2011).*

- **Electrically conducting sheets**, which are drawn from forest-like arrays of carbon nanotube (CNT), can be used as **transparen**t, rapidly **thermally switchable mirage cloaks** and as inexpensive optical scanners.
- This **invisibility for light** oblique to the CNT sheet is caused by the **mirage effect**, in which a thermally generated **refractive index gradient** bends light array from an object.
- Extremely **low thermal capacitance** and **high heat transfer ability** of CNT sheets enable high frequency modulation of sheet temperature over a wide range, thereby providing a sharp, rapidly changing gradient of refractive index in surrounding liquid or gas.

Time Magazine's issue on 50 Best Inventions of 2011

Cloaking



BIO-INSPIRED SYSTEMS: *BEYOND CURRENT VISION*

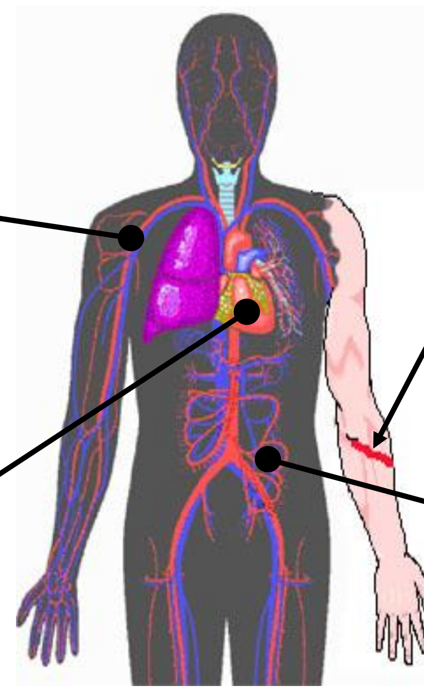
VISION: *EXPANDED*

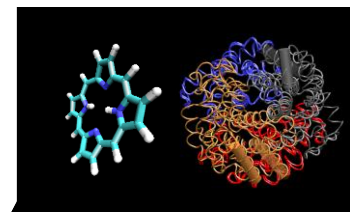
- Biomimetics
- Design for Coupled Multi-functionality
- Nano-materials
- Multi-scale Model
- Micro- & Nano-Devices
- Manufacturing Sci
- Neural Network & Information Sci

AUTONOMIC AEROSPACE STRUCTURES

- *Sensing & Precogn*
- Self-Diagnosis & *Act*
- Self-Healing
- Threat Neutralizat
- Self-Cooling
- *Self-Powered*

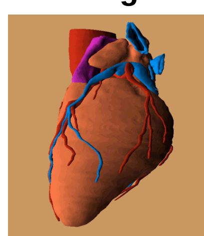
FUNCTIONS OF INTEREST





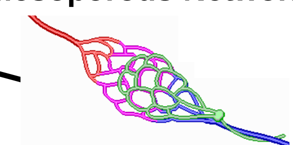
Self-Regulating Function

Active Regulation



Self-Generating Function

Mesoporous Networks



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AFRL

Design by Nature:
BONE REMODELING

Resorption vs Ossification; 4~20% renewal per year;
Subjecting a bone to stress will make it stronger

US-Europe Workshop on Structural Regeneration (27-28 June 2012, Venice)

Co-organized by AFOSR, ARO, U Illinois & Max Planck Inst.

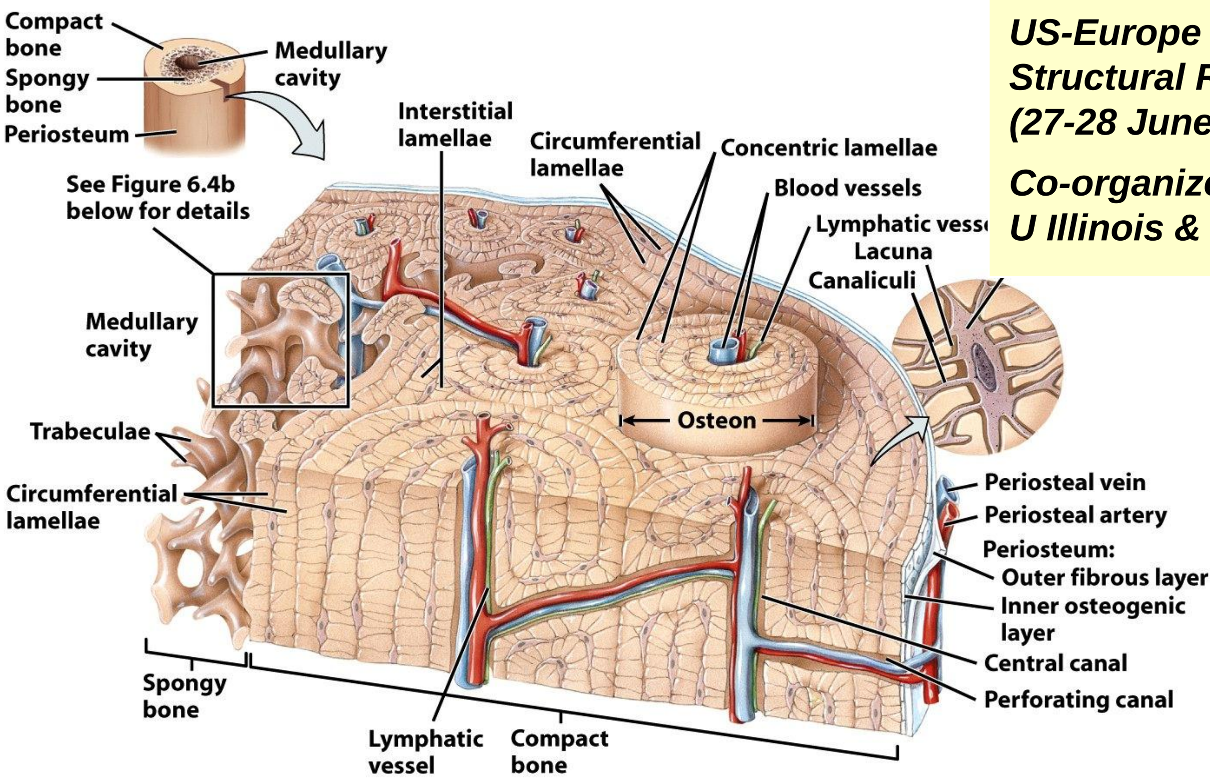
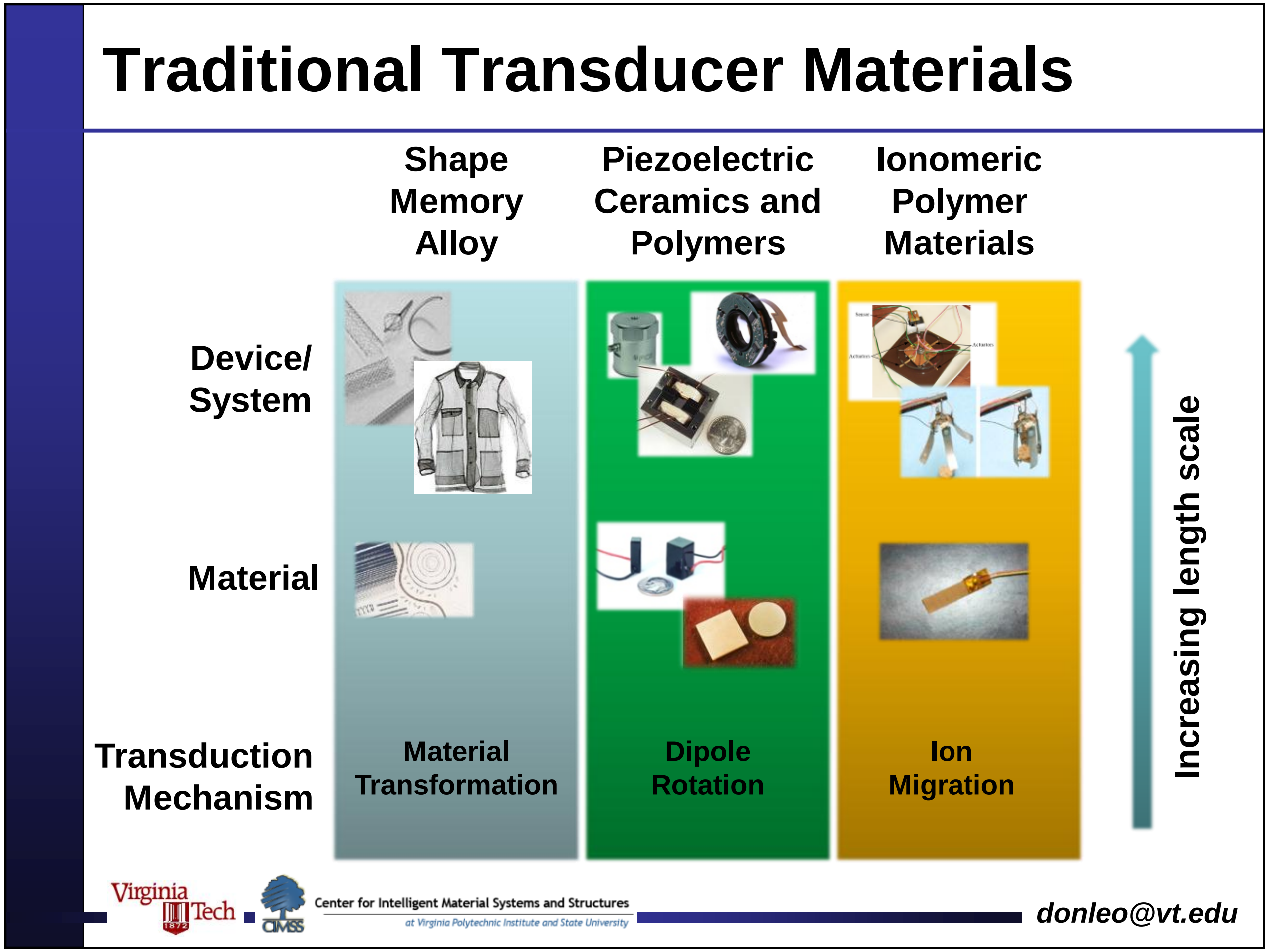


Fig. 6-4a Anatomy and Physiology: From Science to Life © 2006 John Wiley & Sons

ENGINEERED DEVICES:
BEYOND CURRENT VISION



ENGINEERED DEVICES:
BEYOND CURRENT VISION

Traditional Transducer Materials

Device/ System

Material

Transduction Mechanism

Virginia Tech — CIMSS — Center for Intelligent

The question we are studying …

How can we use biomolecules to make completely new types of materials for engineered devices?

Device/ System	Sensors, Energy Capture and Conversion, Color Changes
Material	Durable, Robust, Easy to Manufacture
Transduction Mechanism	Channels, Pumps, Transporters

Increasing length scale

Virginia Tech — CIMSS — Center for Intelligent Material Systems and Structures at Virginia Polytechnic Institute and State University

donleo@vt.edu

SUMMARY

- **The program is fully focused on the establishment of advanced multi-functional aerospace structures.**
- **A major progress has been made in pursuing a new vision for autonomic/reconfigurable systems and providing research support for baseline multifunctional materials and microdevices.**
- **Multi-disciplinary research initiatives are concluded successfully for *"self-healing," "structurally integrated energy harvest/ storage capabilities,"* "energy harvesting from aerospace environment," and *"load bearing antennas."***
- **Three initiatives are in progress for *"neurological system inspired sensory network"* (MURI '09), *"reconfigurable multi-functional structures"* (DCT'09) and *"high-rate deformation"* (CoE'12).**
- **New initiatives are planned for *"biomolecular autonomic material systems," "hybrid energy harvesting"* and *"neutralization of threats"* in collaboration with AFRL/AFOSR colleagues.**