Dynamics, Control and System Diagnostics
CDS&E - EFRI

Massimo Ruzzene

Division of Civil, Mechanical and Manufacturing Innovation (CMMI)

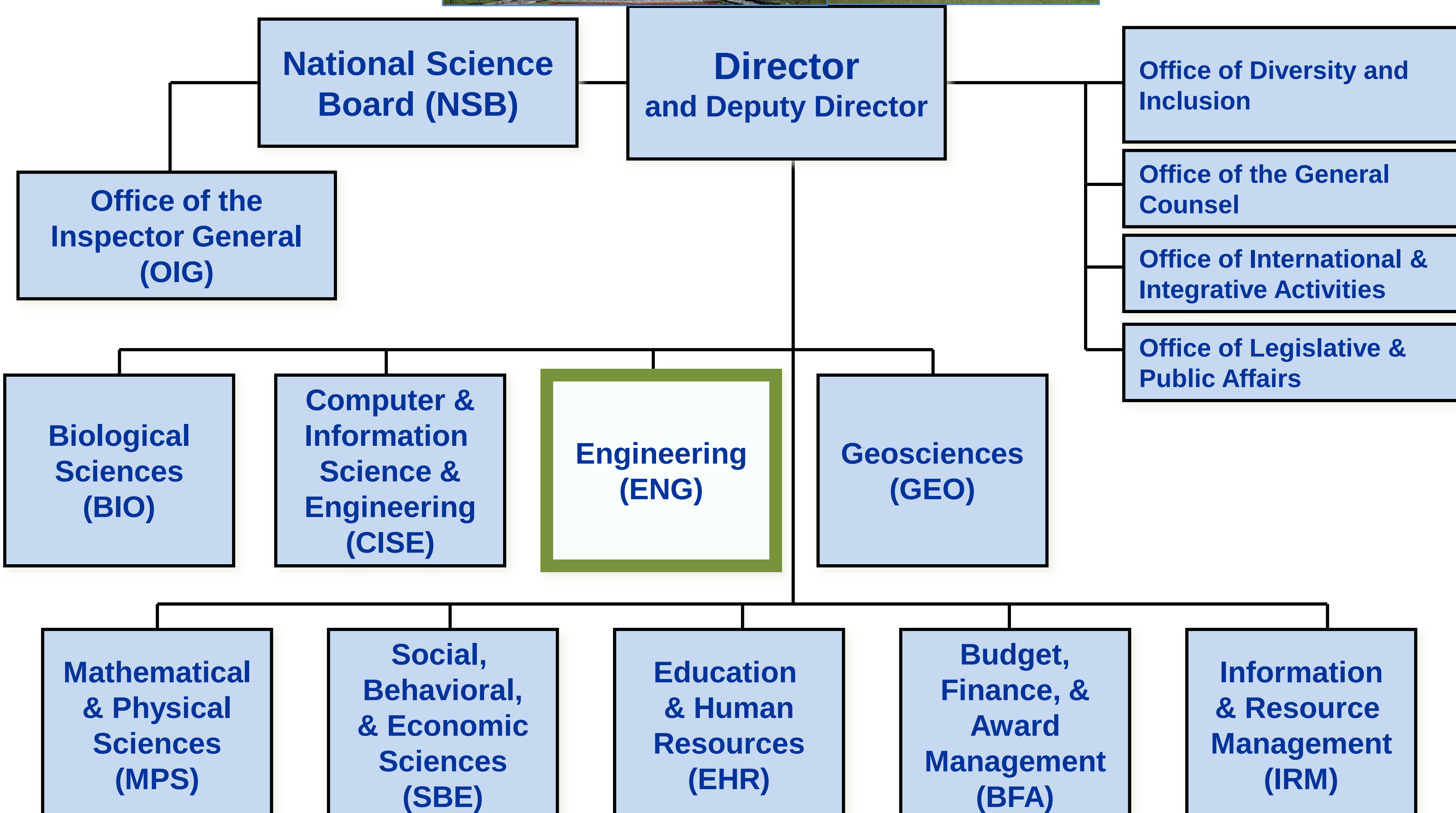
National Science Foundation

Meeting of the
US National Committee on Theoretical and Applied Mechanics
April 22, 2016 – Washington DC

National Science Foundation

- NSF is not a "mission agency"
- Our goal is to promote and enable high quality in education, particularly in the higher education system, and particularly in the sciences and engineering
- In the research divisions, our mechanism is the research grant

National Science Foundation



NSF
Directorate for Engineering (ENG)

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Grace Wang, Deputy Assistant Director

Emerging Frontiers and Multidisciplinary Activities (EFMA)
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Innovation Corps
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Mihail Roco

Program Director for Evaluation & Assessment
Alexandra Medina-Borja

Engineering Education and Centers (EEC)
Mario Rotea

Chemical, Bioengineering, Environmental, and Transport Systems (CBET)
JoAnn Lighty

Civil, Mechanical, and Manufacturing Innovation (CMMI)
Deborah Goodings

Electrical, Communications, and Cyber Systems (ECCS)
Samir El-Ghazaly

Industrial Innovation and Partnerships (IIP)
Barry Johnson

CMMI Mission

"To promote the progress of science; advance the national health, prosperity, and welfare; and to secure the national defense…" by supporting fundamental, transformative research and education in support of

- Advances in manufacturing, design and use of engineering materials, and building technologies across scales from nanometers to kilometers,
- Advances that improve the resilience and sustainability of the nation's civil infrastructure, including reduction of risk and damage from natural and human-induced disasters, and
- Advances in engineering mathematics, engineering decision-making, and systems control and engineering

Civil, Mechanical, and Manufacturing Innovation (CMMI)

Senior Advisor
Bruce Kramer

Division Director
Deborah Goodings

Deputy Division Director
George Hazelrigg

Advanced Manufacturing

- **Manufacturing Machines and Equipment**
  ZJ Pei
- **Materials Engineering and Processing**
  Mary Toney, Alexis Lewis, TBD
- **NanoManufacturing**
  Khershed Cooper

Mechanics and Engineering Materials

- **Biomechanics and Mechanobiology**
  David Fyhrie
- **Mechanics of Materials and Structures**
  Kara Peters
- **Design of Engineering Material Systems**
  Chris Paredis, Mary Toney, Kara Peters

Operations, Design and Dynamical Systems

- **Dynamics, Control and Systems Diagnostics**
  Massimo Ruzzene
  Jordan Berg
- **Engineering and Systems Design**
  TBD
- **Systems Science**
  TBD
- **Service, Manufacturing and Operations Research**
  Diwakar Gupta

Resilient and Sustainable Infrastructures

- **Civil Infrastructure Systems**
  Elise Miller-Hooks
- **Natural Hazards Engineering Research Infrastructure**
  Joy Pauschke
- **Geotechnical Engineering and Materials**
  Richard Fragaszy
- **Structural and Architectural Engineering**
  TBD
- **Infrastructure Mgmt. and Extreme Events**
  David Mendonca

DCSD Program

- ~ 200 Unsolicited Proposals/Window
- ~ 50 CAREER Proposals/Year
- 7 CAREER Awards in FY15
- ~ 50 Unsolicited Proposals Awarded in FY15
- ~ 11% / 14% Funding Rate (Unsolicited/CAREER)
- Also REUs, EAGERs, Workshops, Conferences
- **Total FY15 Award Expenditures ~ $22.5M**

What does DCSD fund?

INTELLECTUAL MERIT and BROADER IMPACT

- **IM** must address innovation in:
  - *Modeling*

    Open new classes of physical systems to the tools of dynamics and control
  - *Analysis*

    Investigations that uncover new structure in dynamic behavior
  - *Diagnostics*

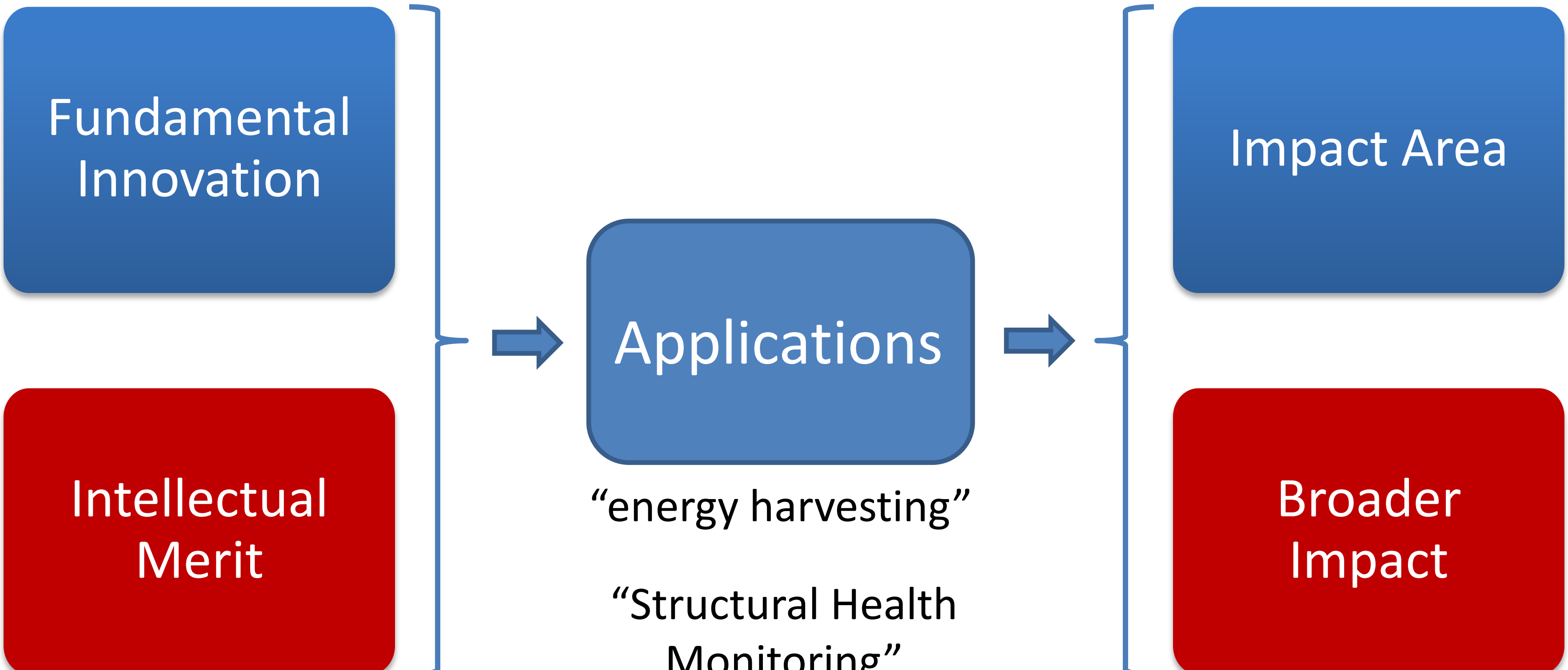
    Methods for acquiring and interpreting information from dynamic behavior
  - *Control*

    Methods for favorably influencing dynamic behavior

Structure of a Research Proposal in DCSD

"Is this a DCSD proposal?"

"Is this a CMMI proposal?"



"energy harvesting"

"Structural Health Monitoring"

"new limit cycle oscillation in fluid/structure system"

"Wave motion in complex materials"

"Energy efficiency"

"Smart infrastructure"

DCSD Foundational Areas

- Dynamical systems
- Acoustics
- Structural dynamics
- Nonlinear dynamics
- Wave propagation
- Multiscale modeling and experiments
- Model-Based Control
- Uncertain and Stochastic Systems, Probabilistic Methods
- Data Compression, Communication and Analysis
- Networks: dynamics and theory
- Path Planning, Guidance, and Navigation

Applications

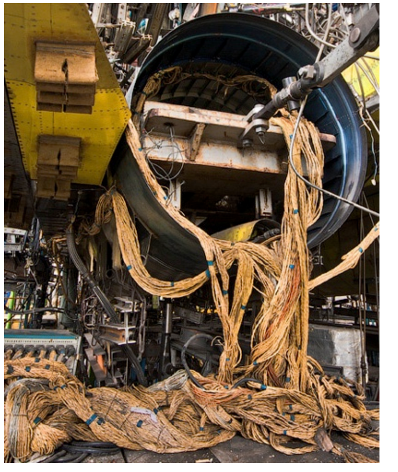
- Autonomous systems
- Structural systems
- Flexible multibody systems
- Structural Health Monitoring
- Biomechanics, Prosthetics and Orthotics
- Dynamics and Control of Micro- and Nanosystems
- Biological systems
- Energy Harvesting
- Micro- and Nano-robotics
- Industrial control systems
- Additive Manufacturing

Impact areas

- Smart Infrastructure
- Advanced Manufacturing
- Industrial, Automotive and Aerospace Systems
- Healthcare
- Sustainable Energy
- Hybrid Vehicles
- HVAC and Smart Buildings
- Ubiquitous Sensing Systems
- Disaster Response and Damage Mitigation

Novel/integrated sensor concepts

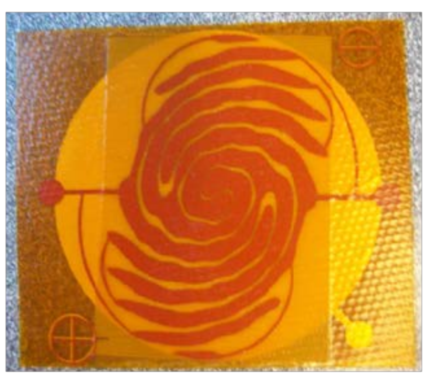
- Legacy sensors (strain gages and ultrasonic transducers) introduce challenges related to:
  - Wiring
  - Hardware requirements
  - Power needs

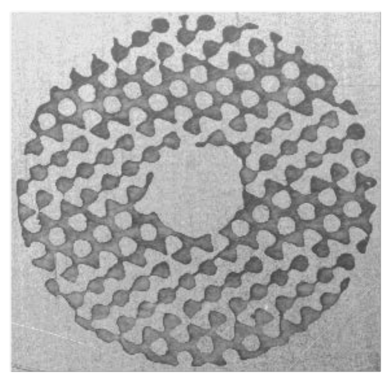


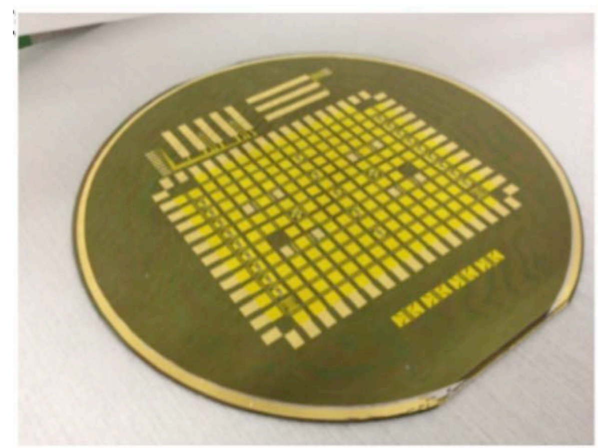
- Basic research on new sensor designs is needed in order to:
  - Simplify health & usage monitoring tasks
  - Enable new functionalities (remote, wireless, distributed, embedded sensing….)

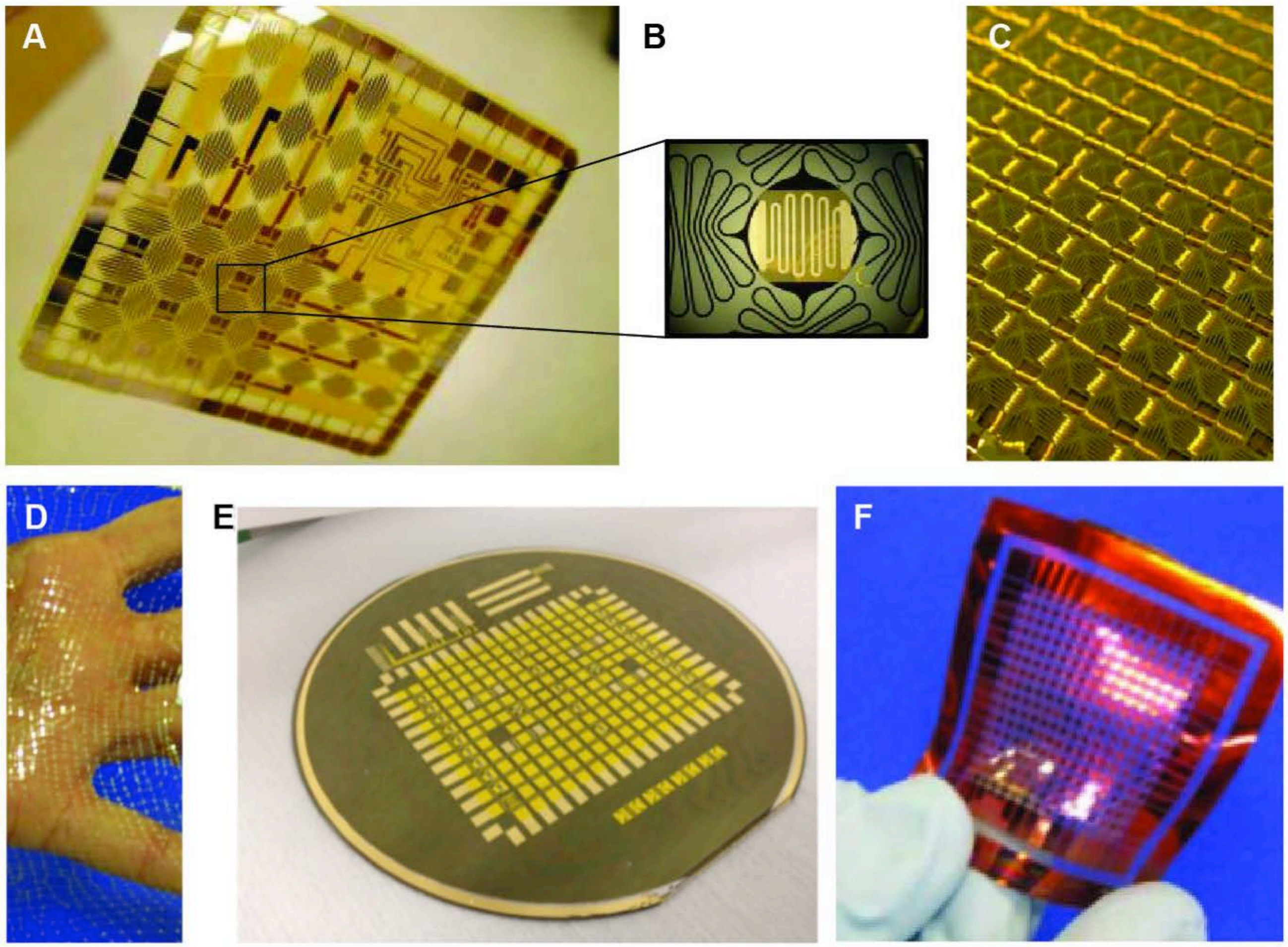
Novel/integrated sensor concepts

- Fundamentally new transducer design concepts need to be developed to enable future diagnostics capabilities
- Opportunities offered by:
  - Additive manufacturing
  - Advanced fabrication technologies
  - Direct write technology for in-situ deposition of sensing material
- Patterning of transducer surface/electrodes leads to novel and tailored functionalities







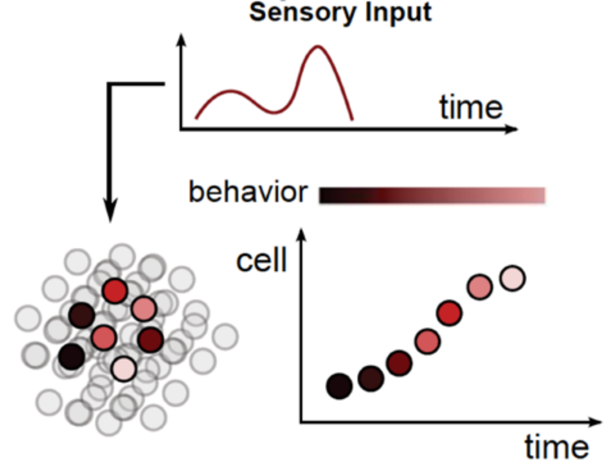


(A) A 16-node sensor network on a wafer can be expanded up to 1,057% in each dimension after release. (B) Optical microscope close-up of the sensor node demonstrating the design of the microwires. (C) A sensor network with 169 nodes before expansion. (D) An expanded 5041-node network is shown in contrast to a hand, which illustrates the flexibility of the membrane. (E) Network before release on a 4-inch wafer. (F) A fabricated 256-node network on polyimide is easily held by hand without damaging the network. It is characterized by 16 µm wide, 50 µm thick microwires.

Courtesy of F.K. Chang – Stanford U.

- Towards Analysis and Control of Dynamic Brain States
  - PI: Ching, S. (Washington U.); Award 1537015

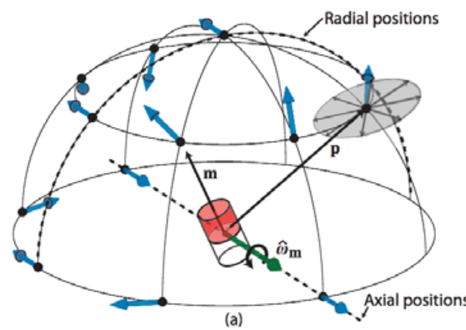
The objective to conduct formal analysis and control of brain networks. The motivation stems from fundamental questions in neuroscience regarding how neural dynamics mediate cognitive function and information processing.

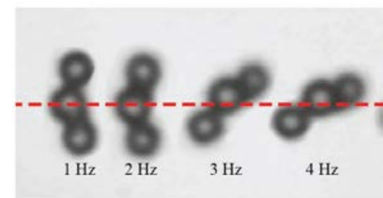


(a)

- Shepherding Biomedical Microswimmers Using Magnetic Fields
  - PIs: Abbott, J. (U. of Utah) and Fu, H. (U. of Nevada); Award 1435827

Study of inherent dynamics of magnetic microswimmers to shepherded in a swarm. Application is therapy and drug delivery

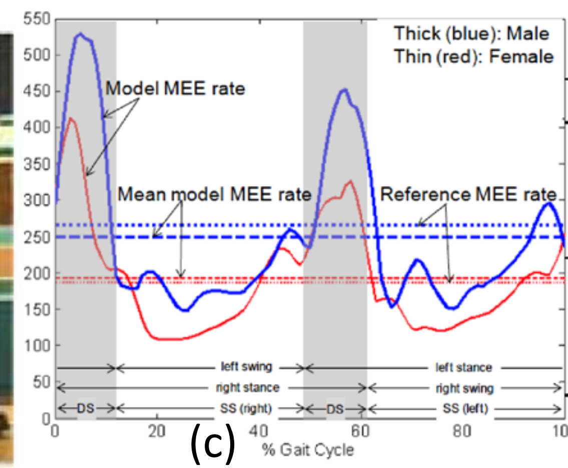




(b)

- Dynamic Modeling and Identification of Human Metabolic Energy Expenditure with Applications to Prosthetic Gait
  - PI: Kim, J. (NYU); Award 1436636

Dynamic model of human metabolic energy expenditure (MEE) and application to energy-efficient prosthetic gait

(c)

Computational and Data-Enabled Science and Engineering (CDS&E)

Computational and Data-Enabled Science and Engineering (CDS&E)

- The CDS&E in Engineering:
  - Research challenges presented to the science and engineering communities by the ever-expanding role of computational modeling and simulation on the one hand, and experimental and/or observational data on the other.
  - Creation, development, and utilization of the next generation of theories, algorithms, methods, tools, and cyberinfrastructure in science and engineering applications.

Computational and Data-Enabled Science and Engineering (CDS&E)

- CDS&E in CMMI :
  - Support the development of novel computational and data tools and environments–beyond that supported by core programs
  - Build on existing cyberinfrastructure and enable major advances in CMMI communities.
  - Topics of special interest:
    - Expanding and leveraging knowledge of biological processes and systems, including biomimicry or bio-emulation, for the design of smart materials, systems and infrastructure.
    - Conducting multi-scale, multi-temporal, multi-physics-based modeling and design of materials systems and structures
    - Exploring and enhancing understanding of human cognitive, behavioral and social processes within engineered systems
    - Transforming the use of optimization methods in CMMI-funded activities by enhanced exploration of solution spaces and exploitation of computational advances to test and evaluate search strategies.

Award Numbers: CMMI-1351487
PI: Michael Olsen
Institutions: Oregon State University
Title: "CAREER/CDS&E: Advanced, 3D Infrastructure Information Modeling Using Lidar"

- The goal of this award is efficiently identify and extract meaningful information from three-dimensional, geospatial models of transportation infrastructure in a holistic, automated framework, enabling broader application. Advanced mapping technologies such as laser scanning produce three-dimensional maps, creating highly detailed scenes that can be virtually explored and queried for a diverse range of purposes including infrastructure management, digital terrain modeling, cultural heritage, flood plain delineation, and landslide detection
- Key scientific questions to be addressed through this research include (1) What inherent attributes of an object and associated representation in laser scan data and supporting imagery are most beneficial to accurately identifying and extracting an object?, (2) How can neighboring features and context of an object help with rapidly identifying it within geospatial data?, and (3) How can an abridged framework be developed to improve information extraction from laser scan data to consider the broad range of transportation objects?

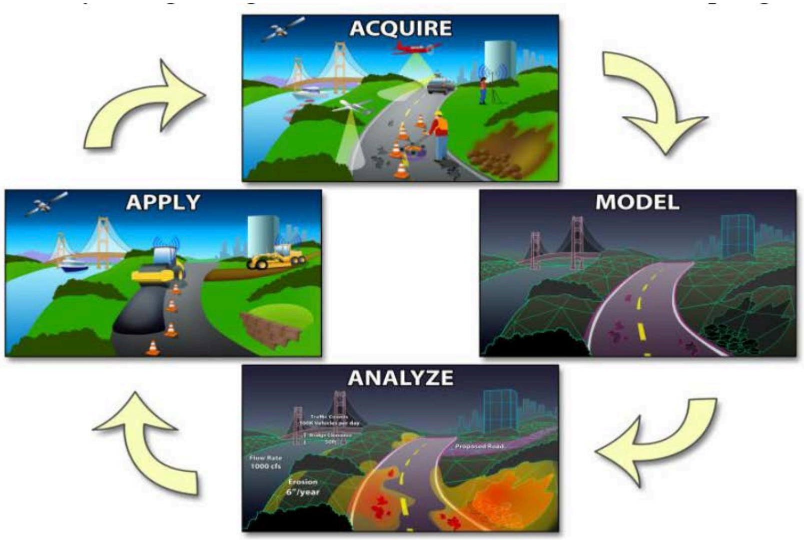


Figure 1. Geospatial Transportation Infrastructure Lifecycle [5].

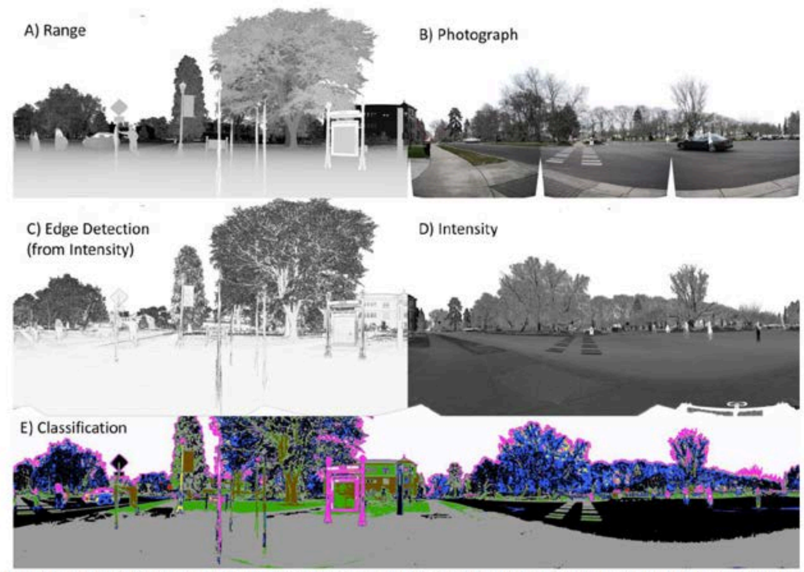
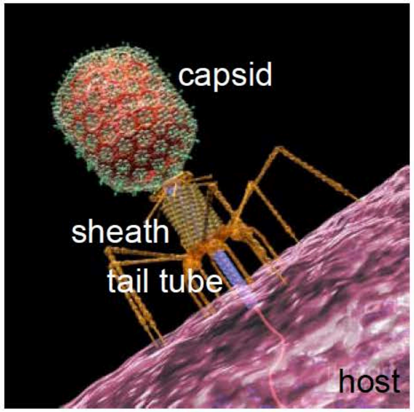


Figure 4. 2D panoramas of scan data. The edge detection (C) and classification in (E) is determined by intensity only. Because computations are done in 2D, they only required milliseconds to complete.

Award Numbers: CMMI-1404747, CMMI-1404818
PI: Noel Perkins, Ioan Andricioaei
Institutions: University of Michigan, University of California-Irvine
Title: “CDS&E/Collaborative Research: Exposing the Injection Machinery Dynamics of Bacteriophage T4 through Multi-Scale Modeling”

- Bacteriophages are viruses that infect bacteria and they are the most abundant organisms on our planet. They are also sophisticated machines that exploit mechanics as vividly illustrated by bacteriophage T4 which injects its DNA into a host through an amazing protein machine. This research will answer fundamental questions regarding how the injection machinery works using novel computational modeling methods. The objective of this collaborative project is to combine continuum models and large scale all-atom molecular dynamics simulations to arrive at a multi-scale model that captures the dynamics of the T4 injection machinery.
- This research lies at the intersection of mechanical engineering, molecular biophysics and computational science and has direct implications to advances in nanotechnologies, which aim to harness viral machinery for useful purposes for human health.



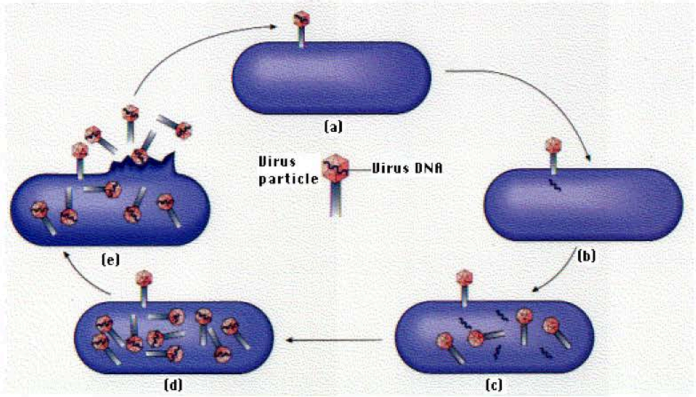


Figure 1: (left) Tailed bacteriophage T4 docked on host [source: http://images.fineartamerica.com/images-medium-large/bacteriophage-t4-injecting-russell-kightley.jpg]. (right) The (lytic) life cycle of tailed bacteriophages including (a,b) docking (adsorption) and genome ejection; (c) genome replication and translation and the assembly of immature virus particles, (d) particle maturation, and (e) release from host (via lysis) [source: http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/L/Luria.html].

Award Numbers: CMMI-1403844
PI: Achintya Haldar
Institutions: University of Arizona

Title: “CDS&E: Theoretical Foundation and Computational Tools for Complex Nonlinear Stochastic Dynamical Engineering Systems - A New Paradigm”

- Engineered structures excited by dynamic loadings, including natural events like earthquakes, cause enormous damage in terms of loss of life, property damage, and lost economic activity. Because of the unpredictability of these events, the excitation time histories cannot be known in advance. The cost of designing structures against such excitation is enormous, and there is considerable room for improvement in the current state of knowledge in predicting the response of structures under these conditions. This study will provide a theoretical foundation and computational tools to analyze structures, and thus to improve the efficiency and overall safety of engineering designs. The impact of the study is expected to be multi-disciplinary in nature. However, the immediate major beneficiary will be the engineering profession interested in designing seismic damage-tolerant and risk-consistent structures.

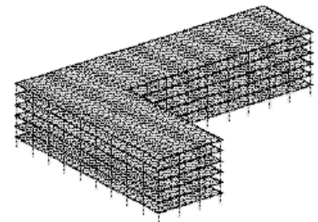


Fig. 1a - Multi-story building

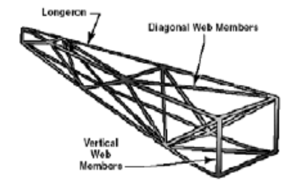


Fig. 1b - Truss for the fuselage of airplane

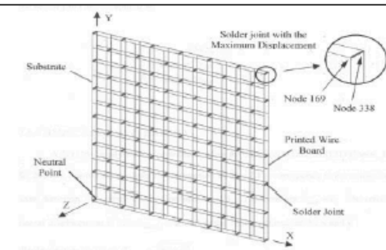


Fig. 1c – Pin layout for PBGA (Whitemack, 2004)

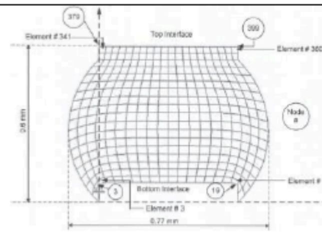


Fig. 1d – FEM mesh for solder ball (Sane, 2007)

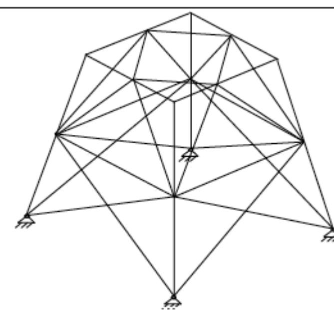


Fig. 1e – Offshore structures

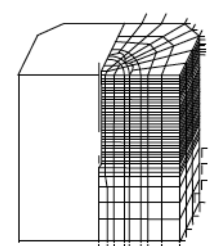


Fig. 1f – Steel-pipe-pile offshore structural system, FEM representation (El-Bordany, Haldar and El-Meligy, 2013)

EMERGING FRONTIERS IN RESEARCH AND INNOVATION 2016 (EFRI-2016)

NEW LIGHT & ACOUSTIC WAVE PROPAGATION

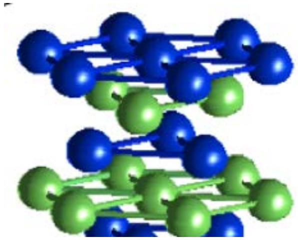
NEWLAW

$15-20M/Year

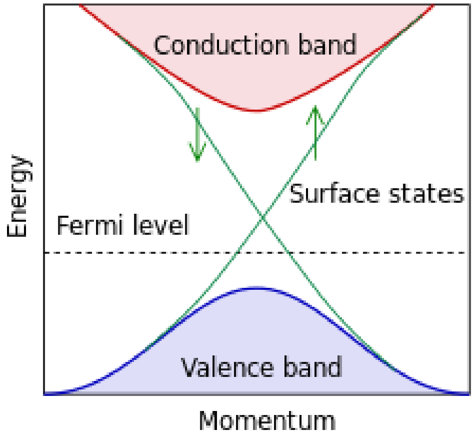
New Light & Acoustic Wave Propagation (NewLAW)

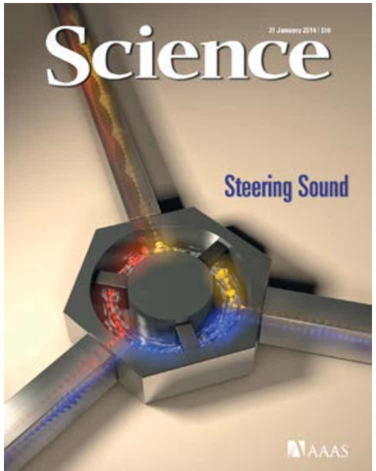
(Background Ideas)

- Recent research in condensed matter (*Topological Insulators*) is inspiring new directions for device engineering based on electronic, photonic and acoustic wave manipulation
- Breaking of fundamental symmetries and reciprocity in acoustic, mechanics, photonics, and radio waves enables one-way propagation, isolation, and wave manipulation and routing;



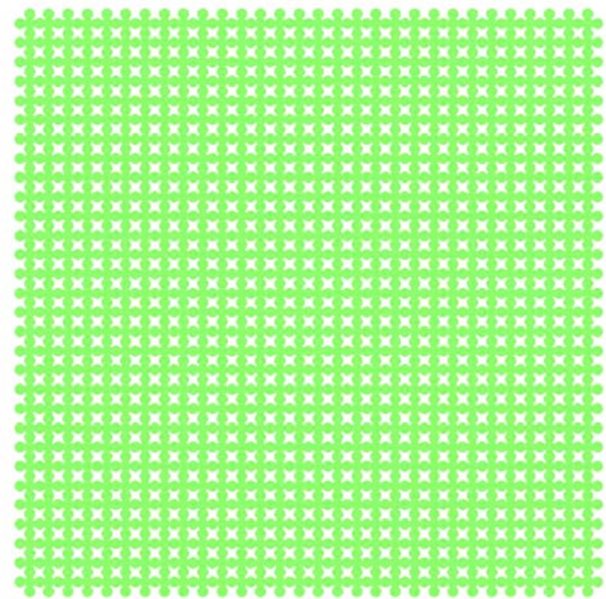
[1]*Nature* **464**, 194-198 (March, 2010)





Overview

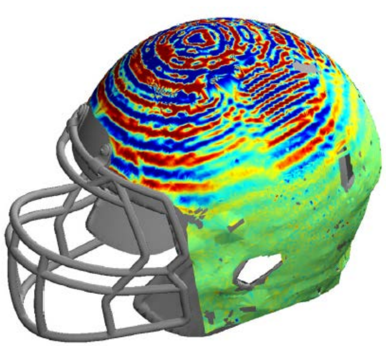
Challenging of the notion of reciprocity, time-reversal symmetry and sensitivity to defects

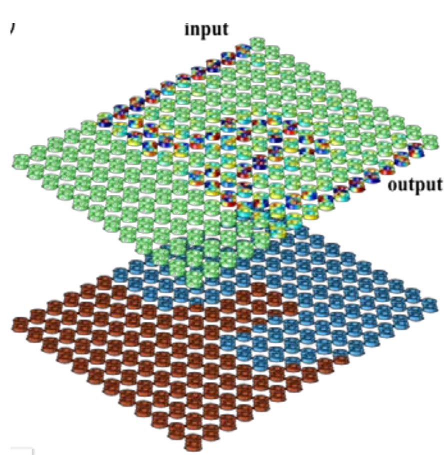


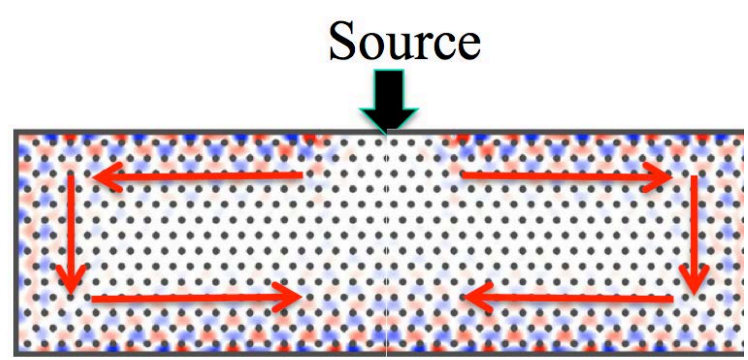
New Light & Acoustic Wave Propagation (NewLAW)

(Expected Transformative Benefits)

- Disruptive approach to design of electronic, photonic and acoustic devices, and enabler of totally new functionalities.
- Applications
  - *Acoustics*: acoustic technologies, such as soundproofing and sonar stealth systems, energy absorbing materials, and imaging
  - *Photonics/electronics*: integrated nanophotonic elements based on topological insulators, full-duplex wireless communications
- Opto-mechanics to provide new research directions with mobile phone as primary potential application.



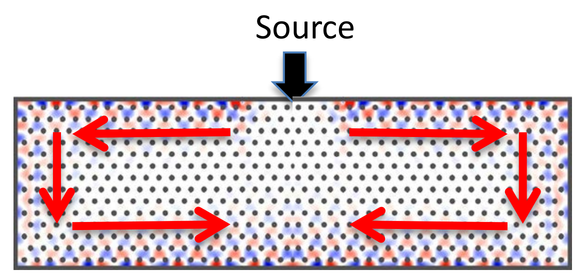




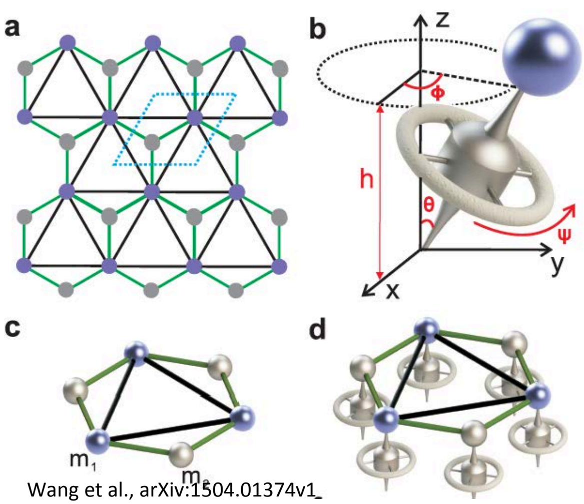
Yang et *al.,* Topological Acoustics, PRL 114, 114301 (2015)

Novelty and transformative aspects Acoustics/Mechanics

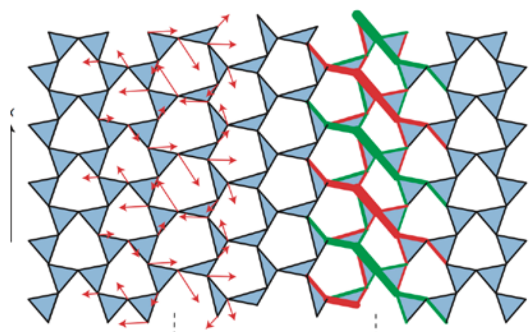
- Exploring passive mechanical approaches
- New "effective" materials
- Dynamic reconfigurations
- Structure might find uses in acoustic technologies, such as soundproofing and sonar stealth systems, energy absorbing materials



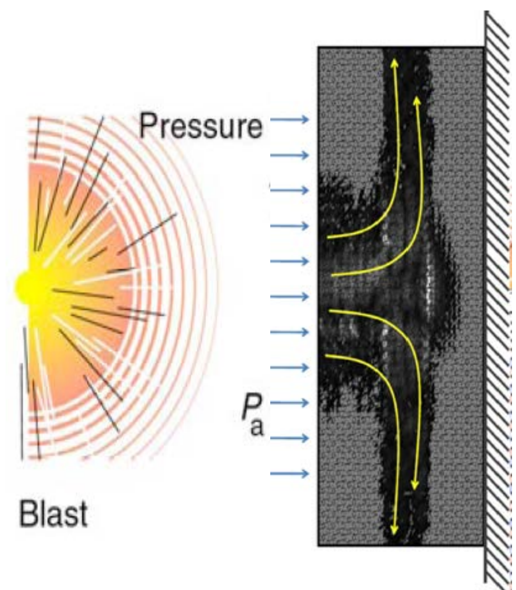
Yang et *al.*, Topological Acoustics, PRL 114, 114301 (2015)



Wang et al., arXiv:1504.01374v1



Topological boundary modes in isostatic lattices
Nature Physics, Vol 10, Jan. 2014.



CMMI Large Grants

CMMI is committed to supporting both single-investigator and team research, including larger-scale unsolicited proposals that are not feasible through a series of smaller projects and are not achievable by a single principal investigator (PI). These larger-scale proposals may request longer time frames (up to five years) and larger budgets (typically not exceeding $1,500,000) that reflect the scope of work. Larger-scale project descriptions must make a convincing case that collaborative contributions will be greater than the sum of each individual investigator's contribution, and are expected to include a Collaboration Plan. PIs are strongly encouraged to discuss the objectives, scope, research team, and budget of larger-scale proposals with the appropriate CMMI program director(s) prior to proposal preparation and submission

CMMI Large Grants

longer time frames (up to five years) and larger budgets (typically not exceeding $1,500,000)

Massimo Ruzzene

mruzzene@nsf.gov

(703) 292 2443 (office) - (571) 213 3909 (cell)