Nanomanufacturing and the NNI Signature Initiative

J. Alexander Liddle

CNST Center for Nanoscale Science & Technology

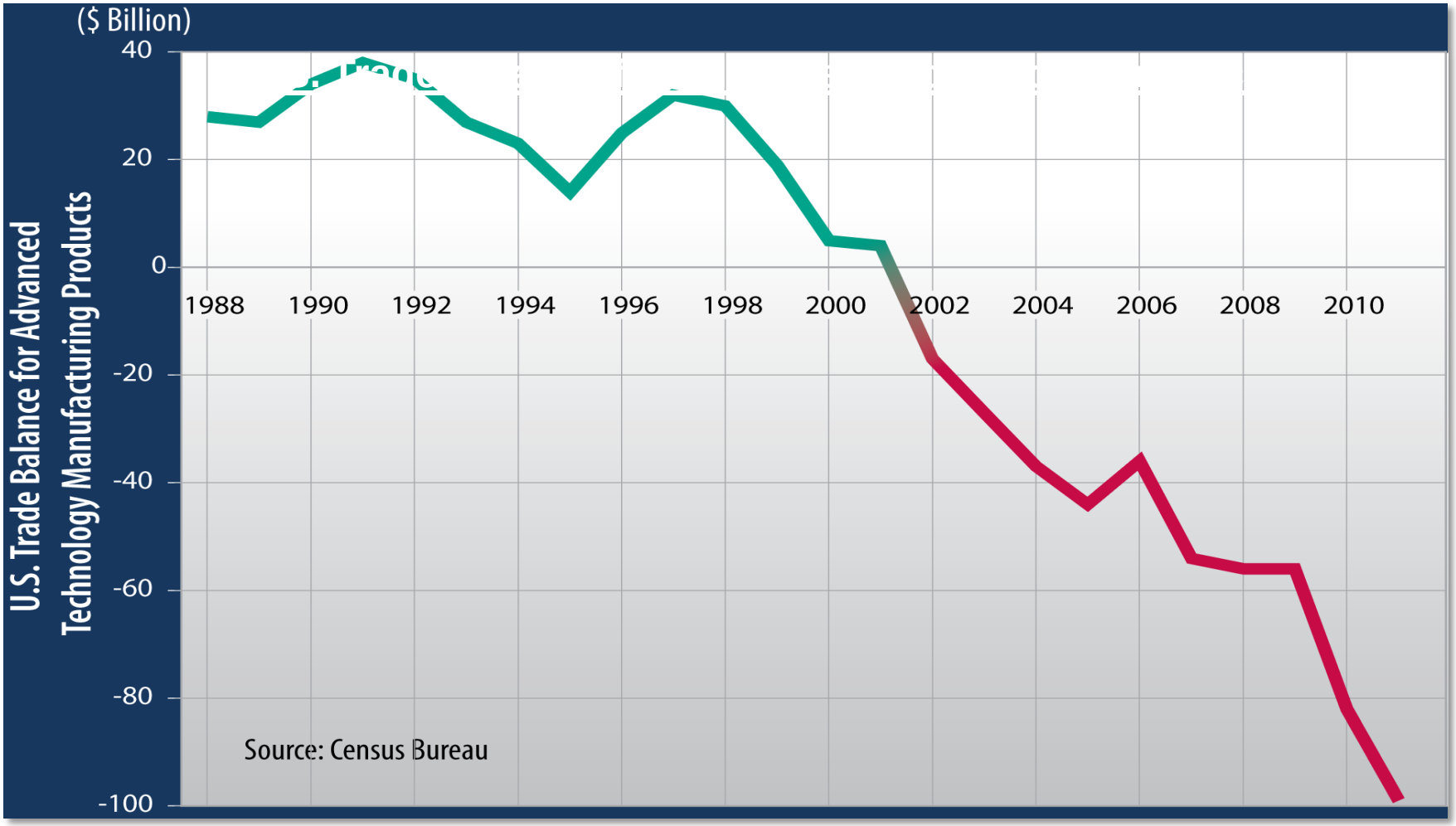
NIST National Institute of Standards and Technology • U.S. Department of Commerce

"The President believes (the following are critical)…

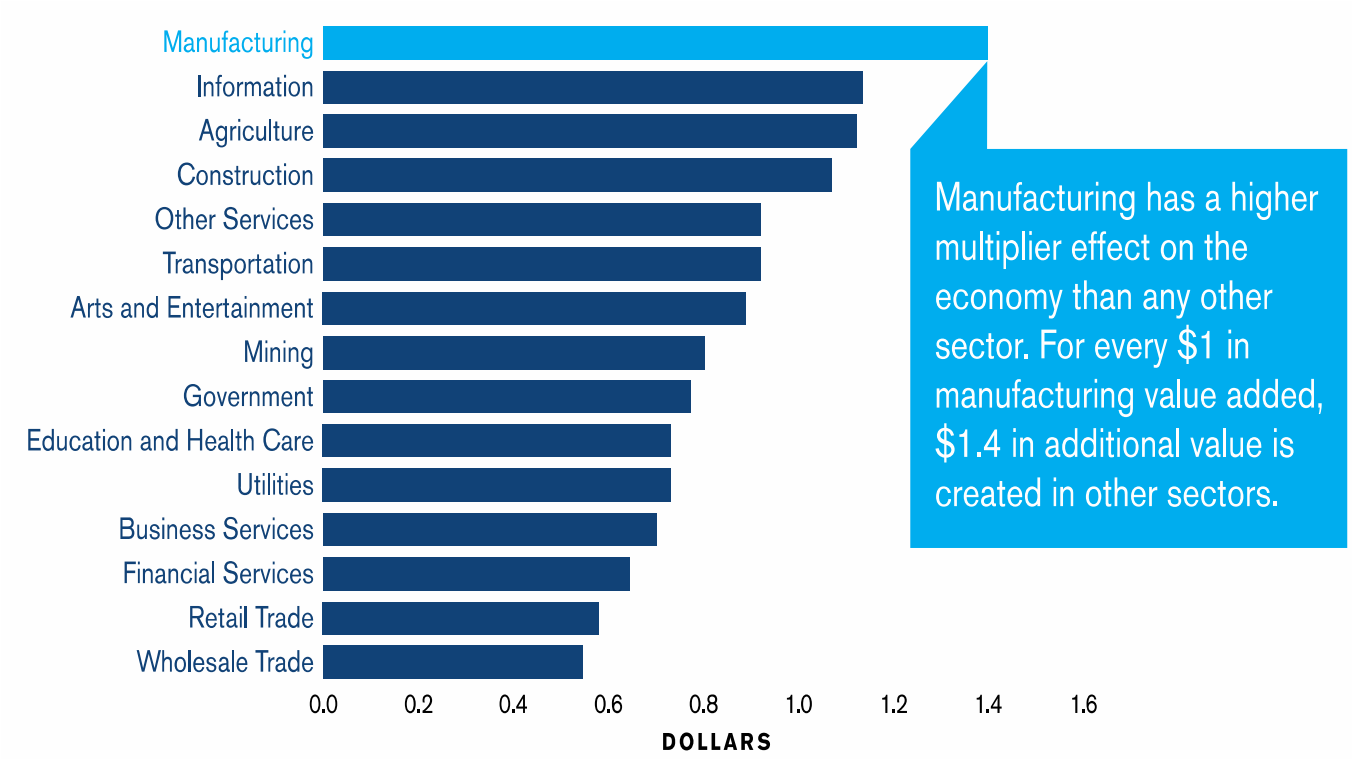
- building domestic manufacturing capabilities in critical national security industries;
- reducing the time needed to make advanced materials used in manufacturing products;
- developing new technologies that will dramatically reduce the time required to design, build, and test manufactured goods."

http://www.whitehouse.gov/sites/default/files/uploads/InnovationStrategy.pdf
http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf

So what IS the problem?

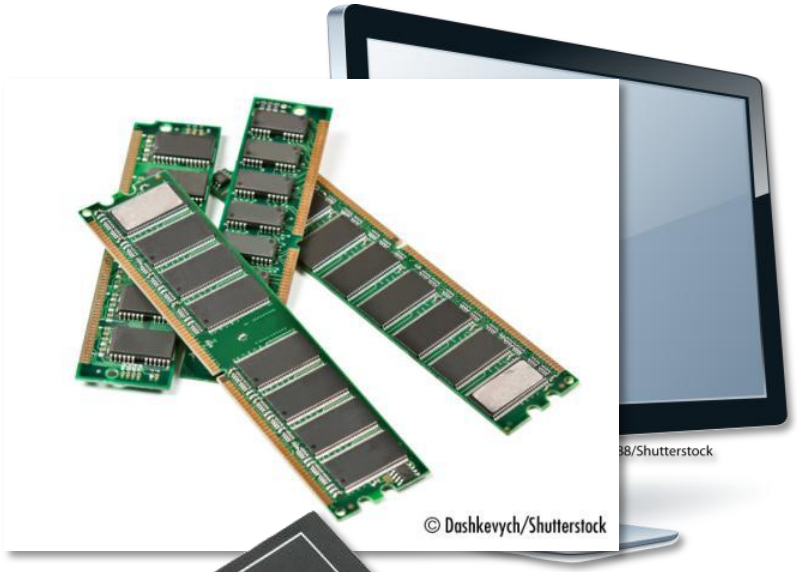


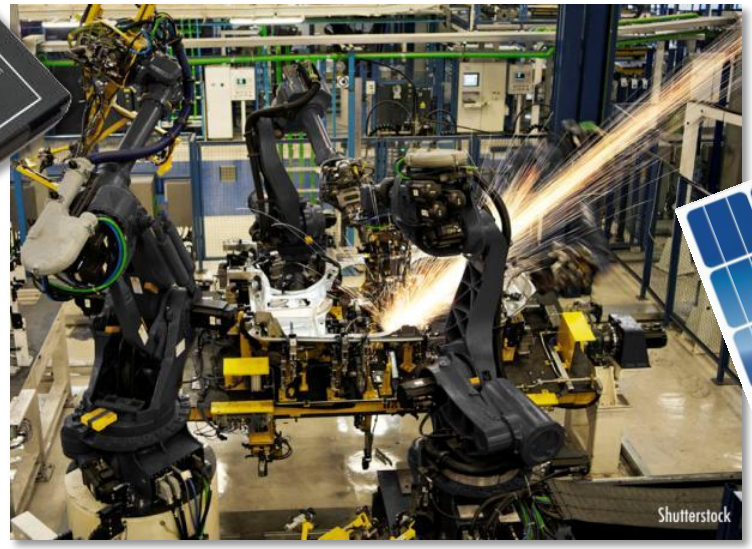
Manufacturing drives jobs throughout the economy

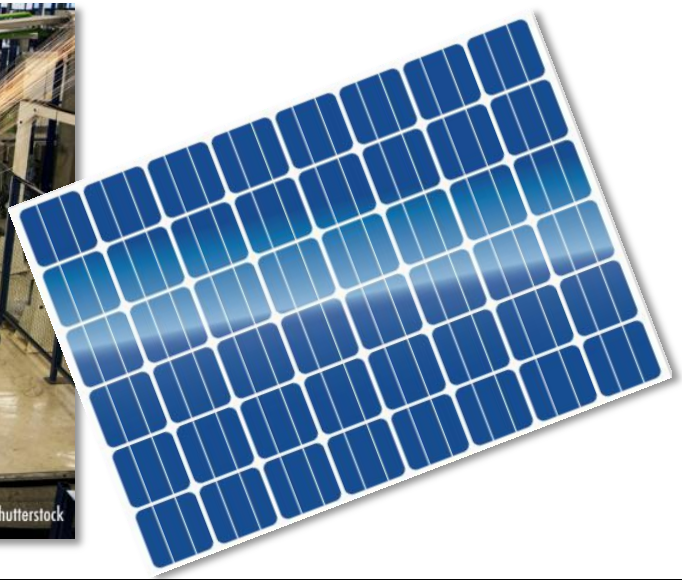


Source: U.S. Department of Commerce, Bureau of Economic Analysis

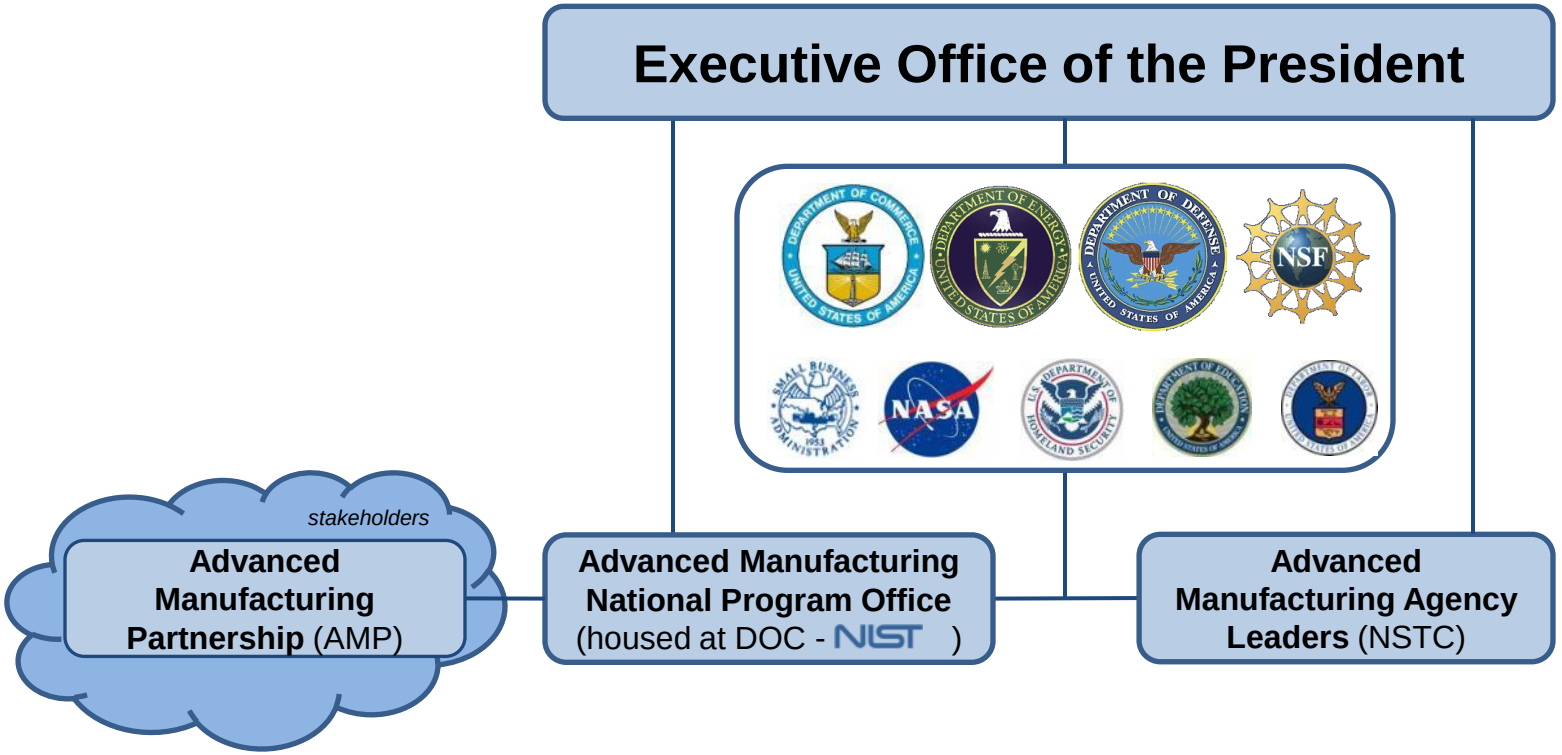
Manufacturing is tied to innovation







Interagency Advance Manufacturing National Program Office (AMNPO)

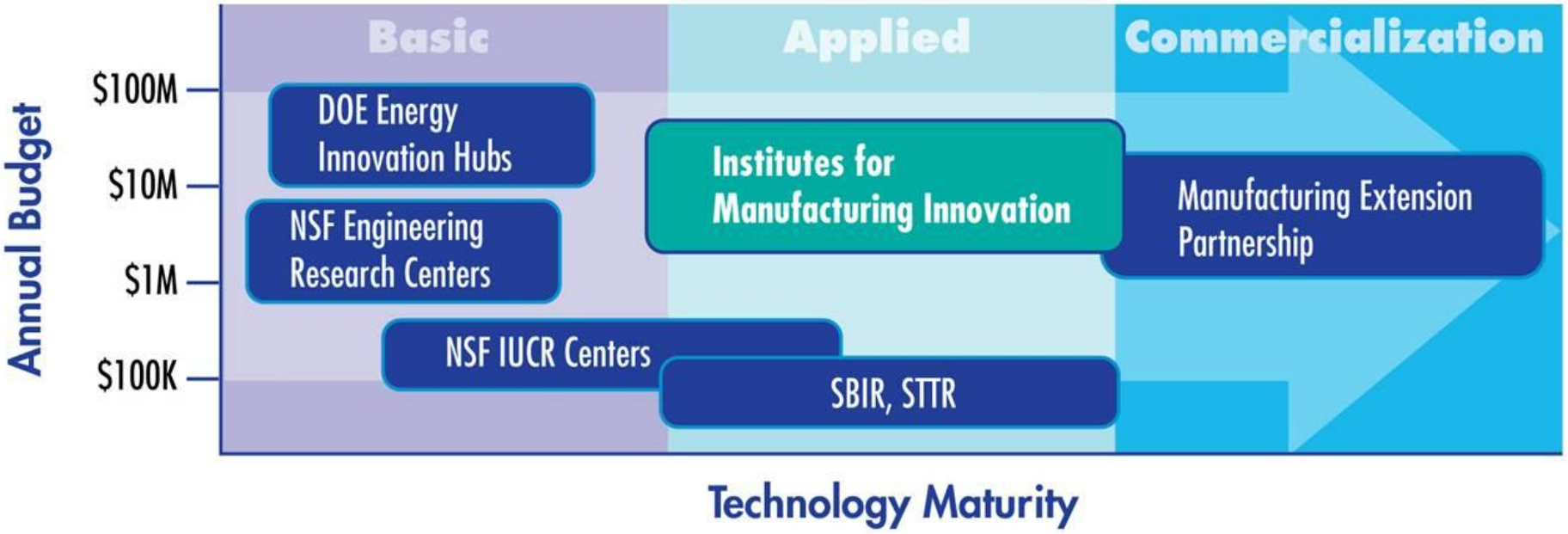


- NPO composed of members from key federal agencies, industry and academia
  - All staff are federal employees via IPA, Federal Fellow or NIST direct hire/short term authority
- Guided by agency leaders within National Science and Technology Council
- Works with agencies to create an integrated interface for advanced manufacturing
- Works with external stakeholders to establish/strengthen AMP private-public partnerships

Focus on Scale Up – The Missing Middle

Basic science
Largely government funded

Commercialization
private sector owned/funded



Partnerships will be critical

- Grantee is self-assembled team of organizations
  - Industry – large + SME's
  - Research organization
- Partners may include
  - Career and technical education institutions (e.g. Comm. Coll)
  - State, regional, or local economic development organizations
  - Professional associations; industry associations; or other not-for-profit organizations.

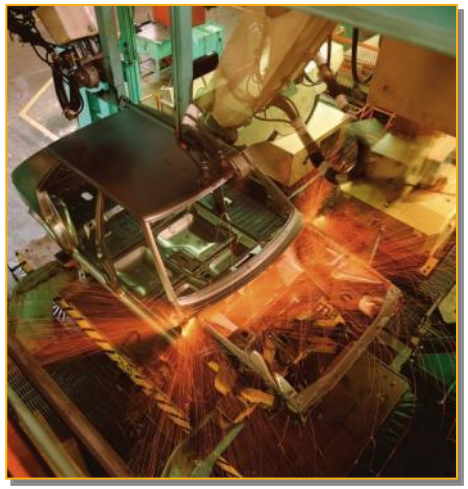
Courtesy: Univ. of Toledo

All ideas welcome – IMI topic category examples

A Manufacturing Process e.g. Additive Manufacturing (IMI FY12 pilot)	**An Advanced Material** e.g. lightweight, low cost carbon fiber composites
An Enabling Technology e.g. smart, sensor enabled manufacturing for productivity and sustainability	**An Industry Sector** e.g. bio-manufacturing to enhance safety, quality, cost and consistency of bio products

Institute Selection Criteria

- Technology focus
- RD&D plan
- Broad Impacts
- Partner resources
- Partner investments
- Self sustainability



Seeking Broad Public Input to Design the NNMI

– *What can you do?*

- Respond to the Request for Information *(coming soon in the Federal Register)*
- Participate in public workshops – *the first event, Designing For Impact I, just took place April 25th at RPI*
- Read updates on manufacturing.gov
- Post on the NNMI wiki
- All ideas welcome

www.manufacturing.gov

ABOUT THE ADVANCED MANUFACTURING NPO

To maintain the partnership's momentum, U.S. Commerce Secretary John Bryson has initiated formation of the National Program Office (Advanced Manufacturing NPO). Hosted by the National Institute of Standards and Technology (NIST), the office will be staffed by representatives from federal agencies with manufacturing-related missions as well as fellows from manufacturing companies and universities.

Also recommended in PCAST's advanced manufacturing report, the Advanced Manufacturing NPO is charged with:

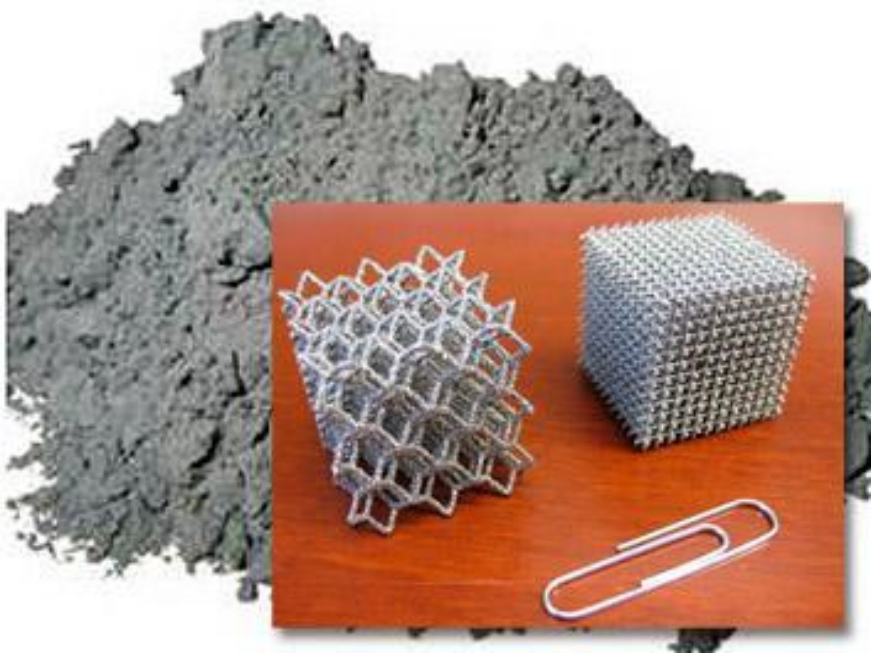
- *Convening and enabling industry-led, private-public partnerships focused on manufacturing innovation and engaging U.S. universities, and*
- *Designing and implementing an integrated whole of government advanced manufacturing initiative to facilitate collaboration and information sharing across federal agencies.*

By coordinating federal resources and programs, the Advanced Manufacturing NPO will enhance technology transfer in U.S. manufacturing industries and help companies overcome technical obstacles to scaling up production of new technologies.

WHO IS PART OF THE ADVANCED MANUFACTURING NPO?

Advanced Mfg Wiki for NNMI

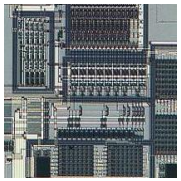
Stay tuned: 2012 Pilot Manufacturing Institute on Additive Manufacturing



May	May	Summer
BAA	Industry Day	$45M

Questions: NNMI2012@wpafb.af.mil

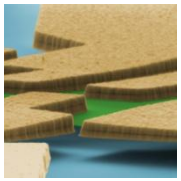
Nanomanufacturing: many things to many people…



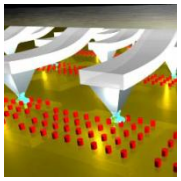
- Make small features on large objects;

- Make nano sized objects;

- Make nanoscale objects to obtain special properties;
  - generally the salient feature of nanotechnology



- Incorporate nanoscale objects in larger objects; or,



- Use nanotechnology to manufacture other things

Offering many benefits…

Novel properties, green, energy efficient

- Catalysis – Lower temperature reactions and reduction of byproducts
- Coatings – Lower friction, superhydrophobic surfaces
- Light-weighting – Reduced rotating, sliding, and conveying weights
- New Materials – Ultra-hard, wear resistant
- Separations – Alternative to distillation or evaporation processes
- Thermal Management – Better heat transfer fluids, thermal barriers
- Engineered Nanomaterials – Thermoelectrics, photovoltaics, batteries

Source: Nanomanufacturing for Energy Efficiency, DoE Workshop Report, 2007

Need bridge between basic science and manufacturing

Science Base

- Carbon-based nanomaterials
- Cellulosic nanomaterials
- Magnetic nanostructures
- Molecular nanoelectronic materials
- Quantum dots
- Optical metamaterials
- Solid-state quantum-effect nanostructures
- Functionalized fluorescent nanocrystals
- Quantum-confined structures

Technology Platforms

Infratechnologies

- Biological detection & analysis tools
- In silico modeling & simulation tools
- In-line measurement techniques to enable closed-loop process control
- Sub-nanometer microscopy
- High-resolution nanoparticle detection
- Thermally stable nanocatlysts for high-temperature reactions

Product

- Carbon nanotubes
- Dendrimers
- Hybrid nanoelectronic devices
- Self-powered nanowire devices
- Nanoparticle fluorescent labels for cell cultures and diagnostics
- Metal nanoparticles & conductive polymers for soldering/bonding
- Nanoparticle sensors

Process

- Epitaxy
- Nanoimprint lithography
- Nanoparticle manufacture
- Rapid curing techniques
- Self-assembling & self-organizing processes
- Scalable deposition processes for polymer-fullerene photovoltaics
- Inkjet processes for printable electronics
- Purification of fluids with nanomaterials
- Roll-to-roll processing

Commercial Products

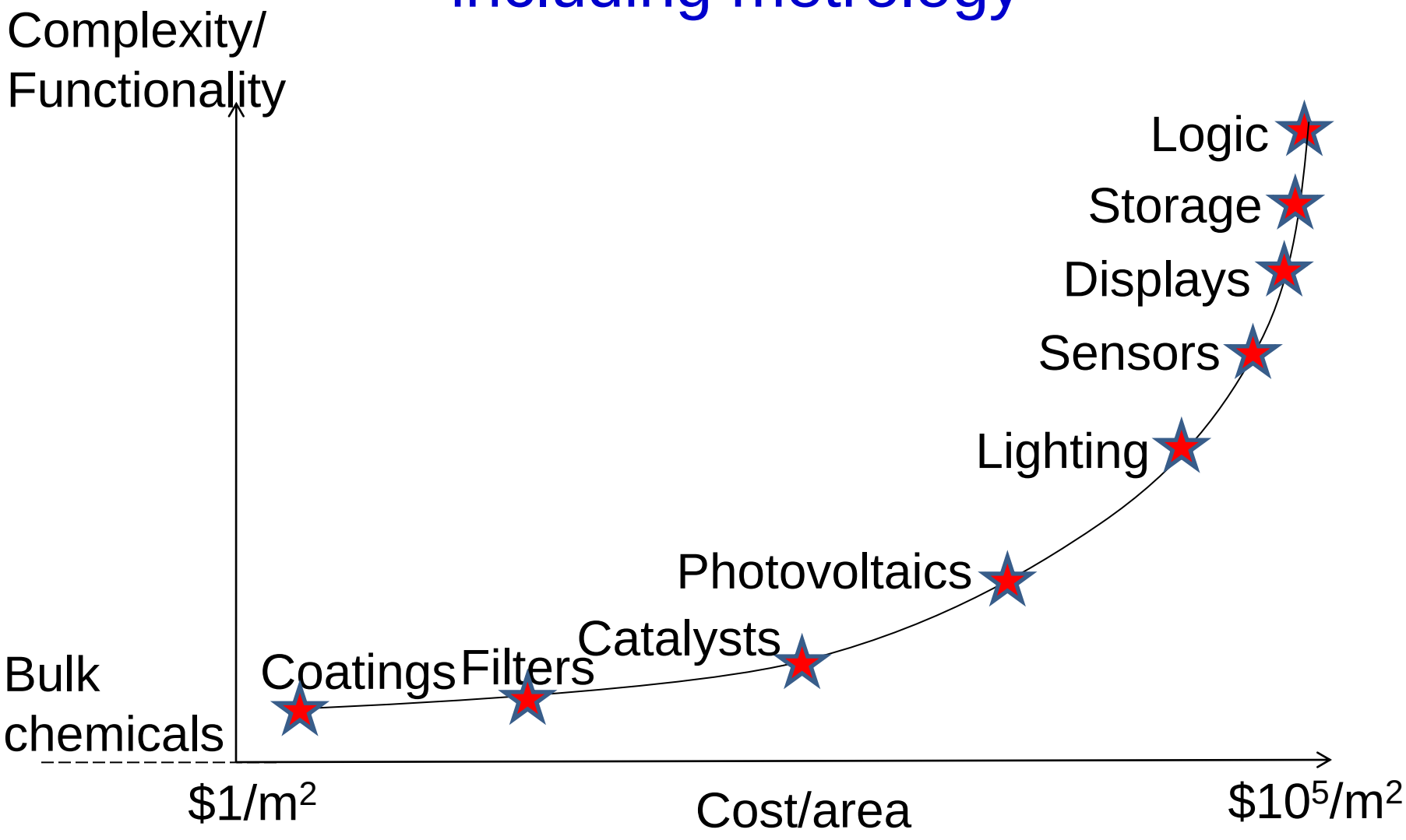
- Hardened nanomaterials for machining/drilling
- Flame retardant nanocoatings
- Sporting goods
- Solar cells
- Sunscreen/ cosmetics
- Targeted delivery of anticancer therapies
- Biodegradeable and lipid-based drug delivery systems
- Self-repairing and long-life wood composites
- Anti-microbial coatings for medical devices

Public Technology Goods

Mixed Technology Goods

Private Technology Goods

Complexity drives manufacturing cost, including metrology



Measurements needed for basic processes & production

Two classes of measurements:

- Detailed, extensive
  - Develop understanding of basic processes
    - E.g. *In situ* observations of carbon nanotube (CNT) growth for process window optimization
- On-line, fast
  - Enable process control during manufacture
    - E.g. Real-time measurement of organic photovoltaic (OPV) coating process
- *Develop core metrology competencies that can be leveraged across a wide range of measurement problems.*
  - *Pursue research into the development of new fabrication techniques in order to gain insight into the coming generations of nanomanufacturing methods and the measurements they will require. In some cases, novel fabrication approaches can enable new measurements.*

NNI Focus on Nanomanufacturing: *Nanomanufacturing Signature Initiative**

Interagency plan to advance the state of nanomanufacturing in strategic areas

- Key requirements: scalable, controllable, sustainable & safe
- Thrust 1: Design of scalable & sustainable nanomaterials, components, devices & processes
  - Formation of consortia: carbon-based nanomaterials (NIST), metamaterials (NSF), cellulosic materials (Forestry Service)
  - Demonstration of materials and processes
  - Technology transfer
- Thrust 2: Nanomanufacturing **measurement** technologies
  - Consortium on metrology for roll-to-roll
  - Fast, robust process control measurement systems
  - Technology benchmarking and transfer with industry

***NNI Signature Initiative: Sustainable Nanomanufacturing: Creating the Industries of the Future**, July 2010

Nanocomposites: A Growing Market

- Global composites industry $88B, U.S. share 36% (16% structural materials market)[1]
  - C-fiber 52.3M kg/yr (additional 18M kg/yr in China after 2010) McConnell, V. "*The Making of Carbon Fiber"*, Composites World, 19 December 2008. & BMW Press Release July 2010.
  - Prepregs from RUSNANO's Project Company to be Used in Russian Aircraft Construction – *Nanowerk* 17 August 2011

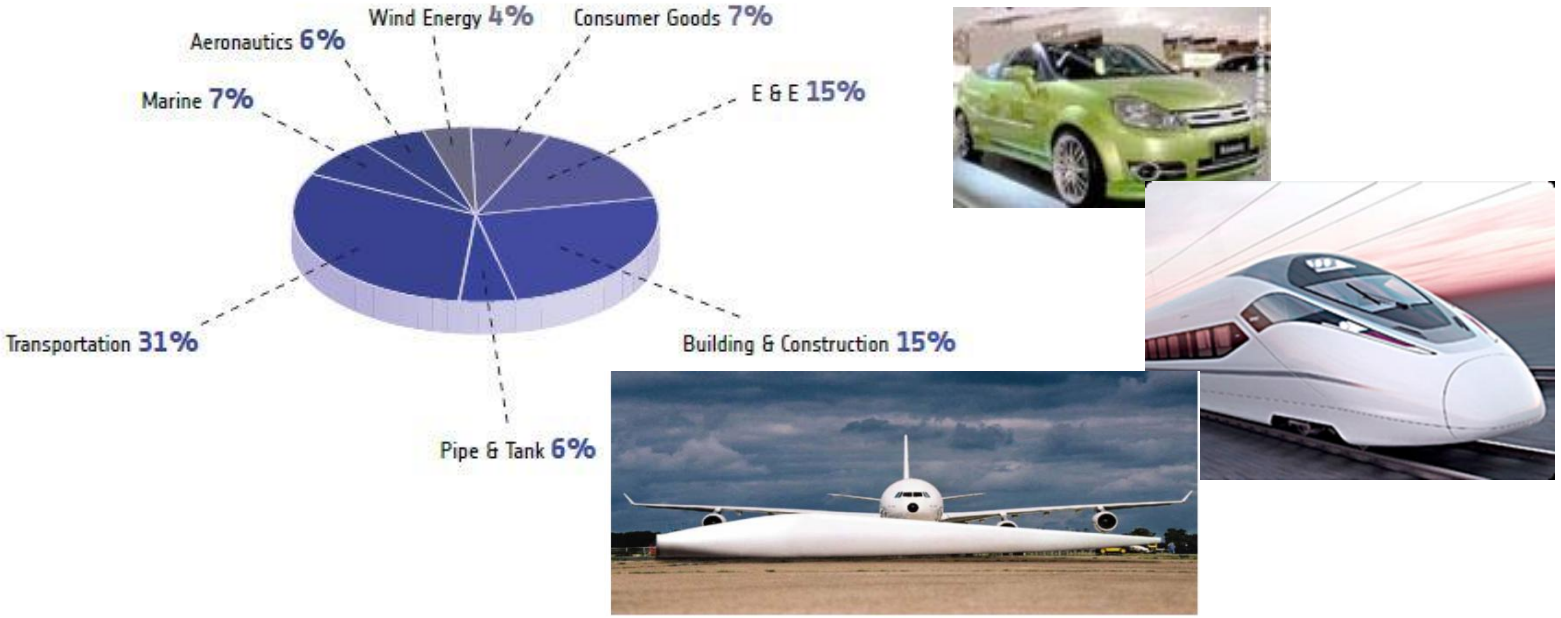
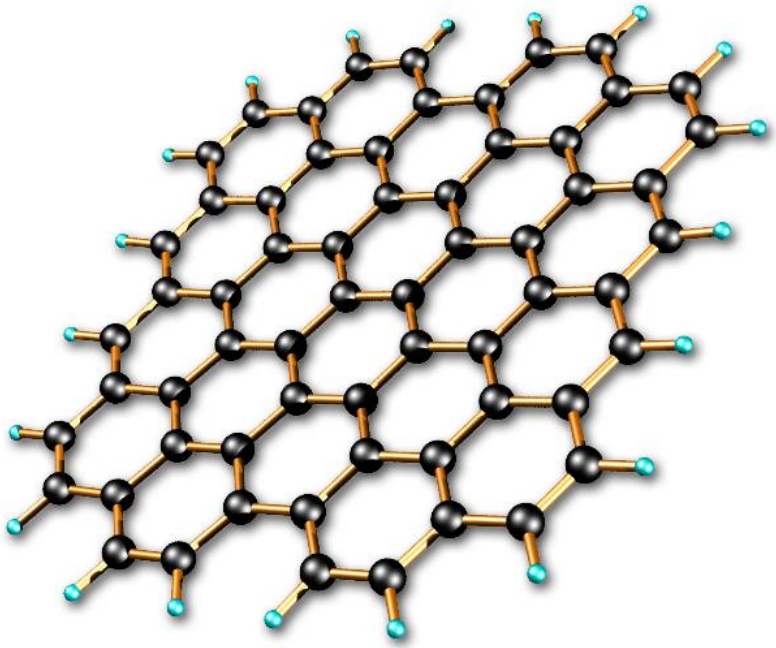


Figure 1: Size of the E 112 rotor blade in comparison to an Airbus 340 (photo courtesy A&R Rotec)

http://www.jeccomposites.com/events/jec-show-americas-2012/jec-show-americas-2012/american-composites-market

Why Are C-Nanostructures Important?

The sp^2 C-C bond



http://www.swarmknowledge.com/

- Modulus:
  - 1.01 TPa ≈ 50 x Steel
- Strength:
  - 100 GPa ≈ 100 x Steel
- Thermal conductivity:
  - 3000 $Wm^{-1}K^{-1}$ ≈ 7.5 x Cu
- Electrical conductivity:
  - 30 nΩ m ≈ Cu
- Multifunctional

Understanding Needs by Listening to Industry

Workshop held at NIST February 28 – March 1, 2011 – part of Signature Initiative on Nanomanufacturing

Over 60 attendees from industry, academia, and government

Measurement Barriers

- Insufficient understanding of the relationship of morphology and individual nanotube properties to composite material performance
- Lack of low-cost, high-throughput measurements for manufacturing

The New Steel?: ***Enabling the Carbon Nanomaterials Revolution: Markets, Metrology, Safety, and Scale-up***
http://www.nist.gov/cnst/thenewsteel.cfm

Lockheed Martin Combines Nanocomposites in Airframe Units, *Azonano*, 5/30/2011

nanocomp TECHNOLOGIES, INC.

DUPONT The miracles of science

IBM

LOCKHEED MARTIN

BOEING

Buckeye Composites A division of NanoTechLabs, Inc.

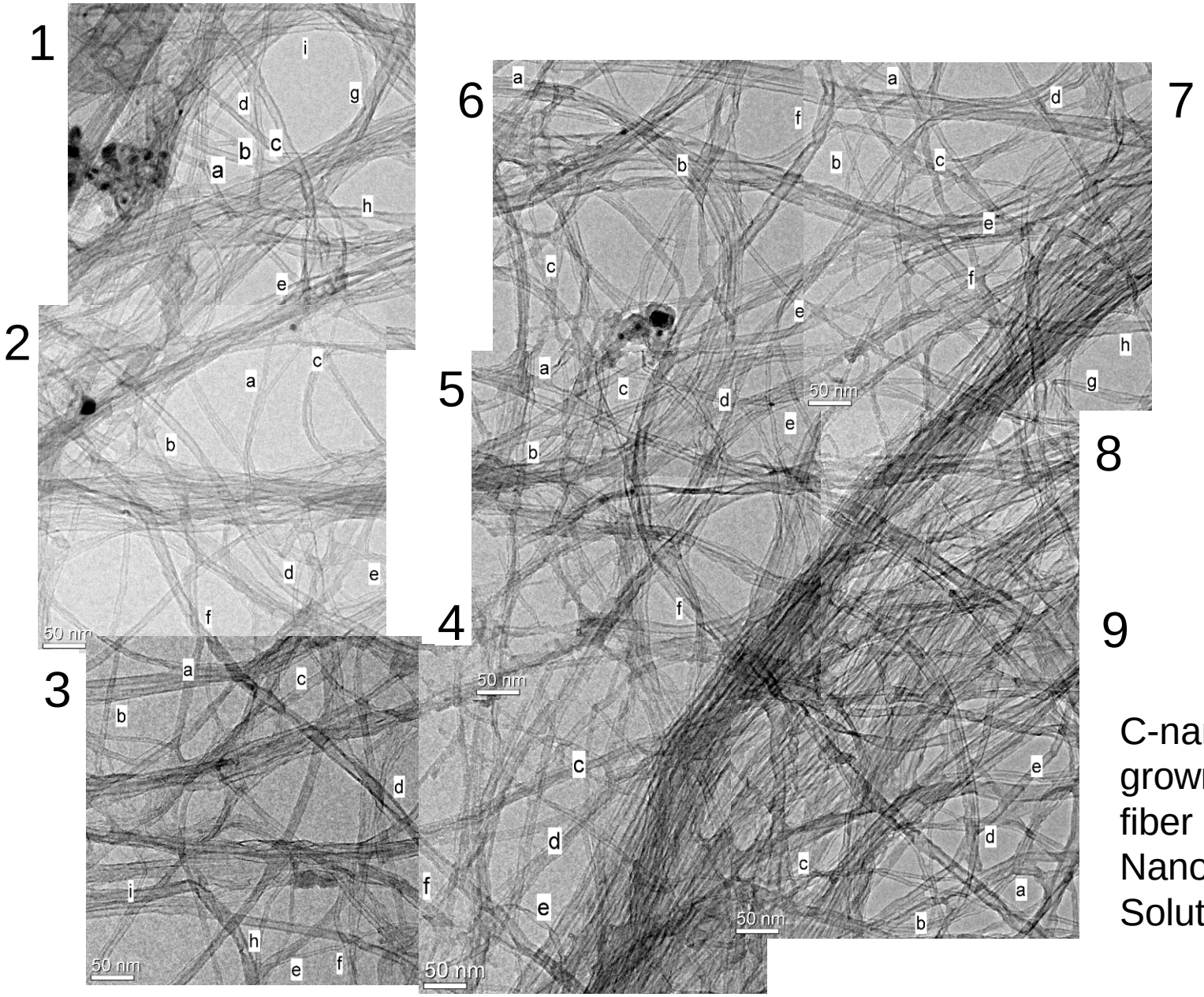
SWeNT SouthWest NanoTechnologies

Workshop Identified Urgent Needs

- Methods for measuring CNT/matrix interface properties
- Descriptors for and characterization of CNT networks
- Novel, non-contact measurement methods that can report on composite nanostructure

- Standardized accelerated ageing tests for lifetime assessment (properties and release of nanomaterials as a function of time)
- Standards and specifications for test methods and measurement data for composite properties

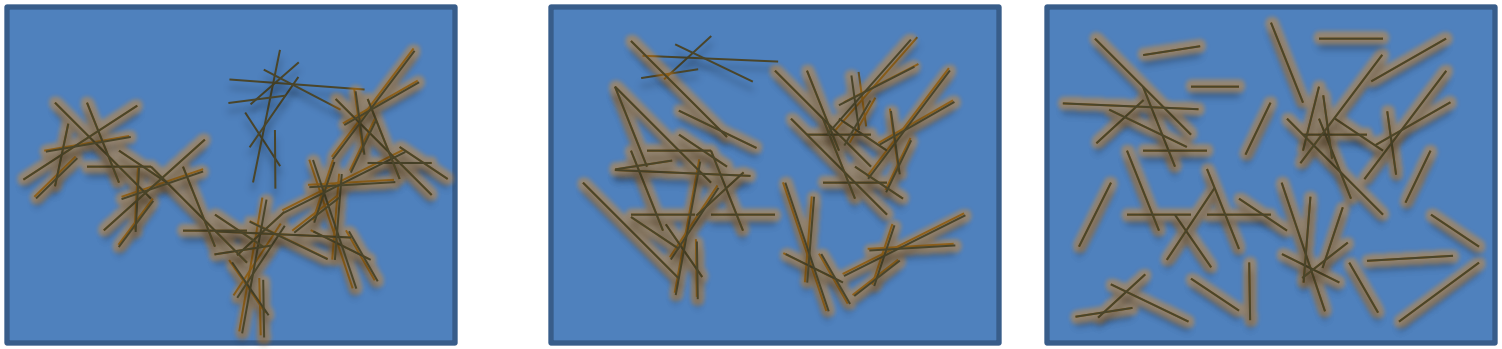
- *Standardized methods for the complete characterization of individual nanotube properties and their statistical distributions (diameter, length, number of walls, chirality, presence/absence of end-caps, etc.)*
- *Standardized measurements of impurity content (species, quantity, morphology)*



C-nanostructures grown on glass fiber (Applied Nanostructured Solutions)

Carbon Nanotube Network Morphology Controls Properties

Constant volume fraction of CNT in polymer matrix



Nanostructured by design | Typical – unconnected clusters | Well-dispersed

Increasing CNT aggregation and network formation

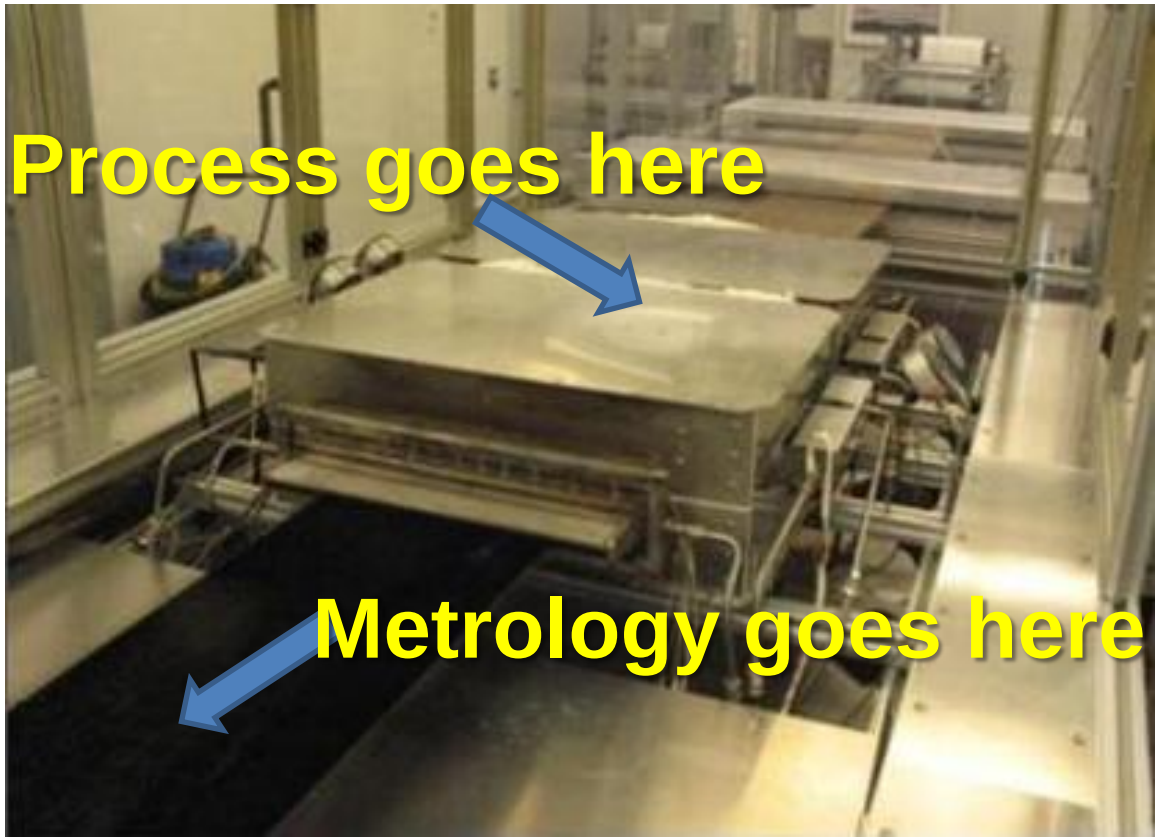
Decreasing CNT percolation threshold

Increasing electrical, thermal properties

Increasing CNT-matrix interphase volume

Increasing high temperature mechanical properties

Production Metrology Must Be Fast, Economical & Sensitive to the Nanoscale



Carbon nanotube (CNT) nanocomposite pilot line at Applied Nanostructured Solutions – nanostructures generated on a meter wide web moving at meters/minute

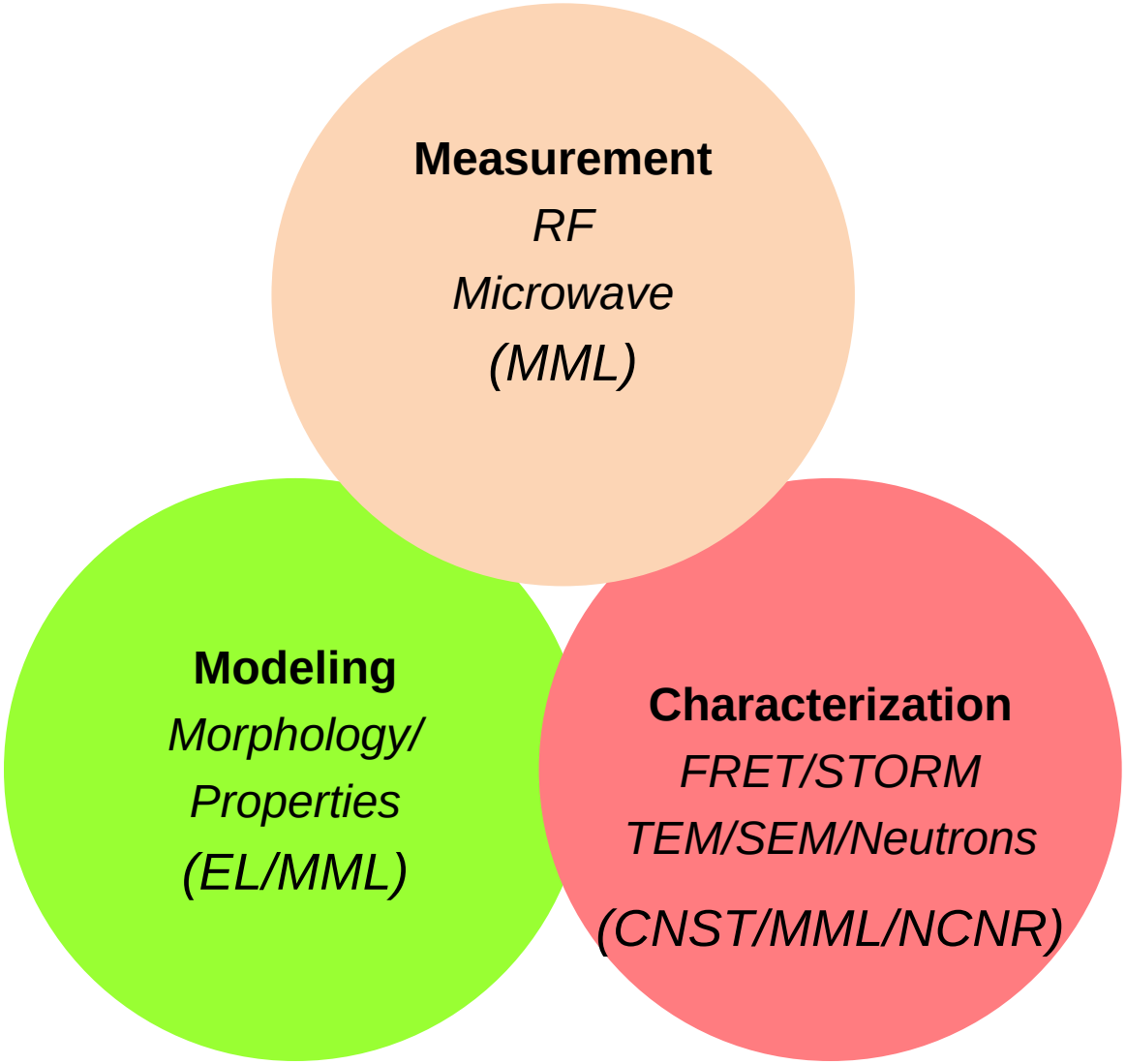
CRADA in place to understand effect of growth conditions on nanostructure morphology and on material performance

Why In-Line Microwave Metrology?

Requirements: non-contact, fast, versatile

- Direct property measurement
  - EM shielding effectiveness – reflection &transmission coefficients
  - Lightning strike resistance – transient electrical conductance/impedance
- Indirect: relate microwave data to morphology, properties, without detailed structural characterization
  - Model critical electromagnetic properties using morphological information from TEM, etc.,
  - Add information from FRET/PALM: interphase, rheology, time-evolution of interface (invisible morphologically)
  - Derive properties such as mechanical integrity and heat transfer – frequency-dependent electrical conductivity
- Microwave signals in reflection (radar) or transmission (new)

How Do We Get There?

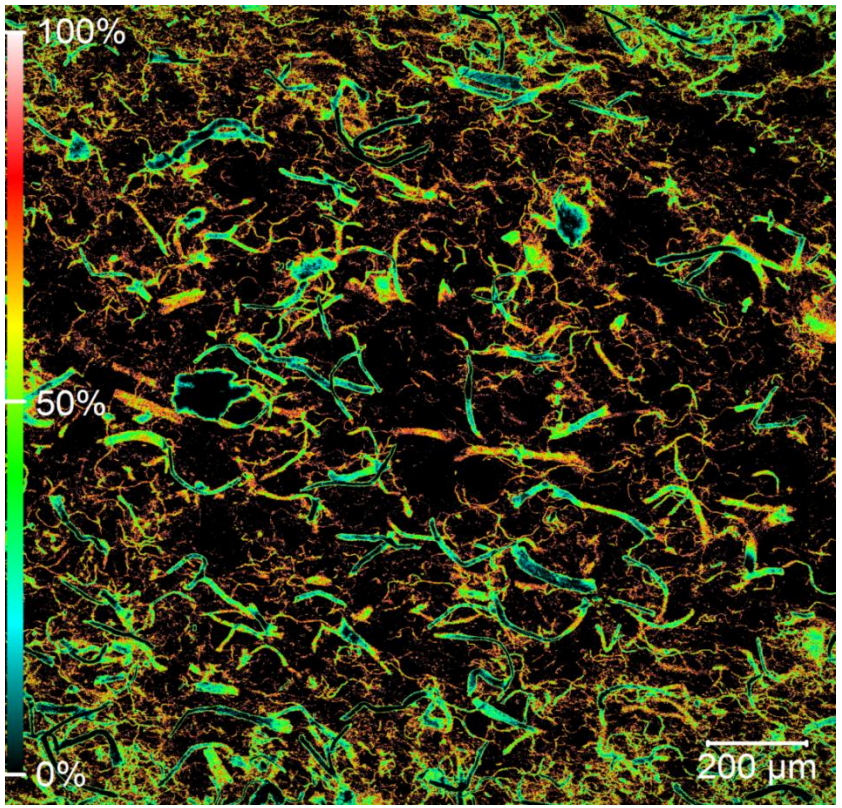


Revealing the Interphase by Förster Resonance Energy Transfer (FRET)

Nanofibrillated cellulose fibers in polyethylene
FRET imaging: reveals interface

Note: Interfacial region can dominate nanocomposite properties with high particle loadings and can evolve over time and under light exposure

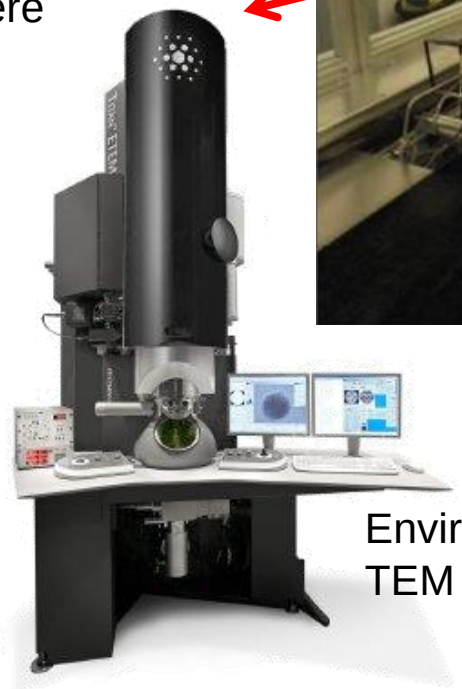
- Few non-invasive probes
- Information required for modeling



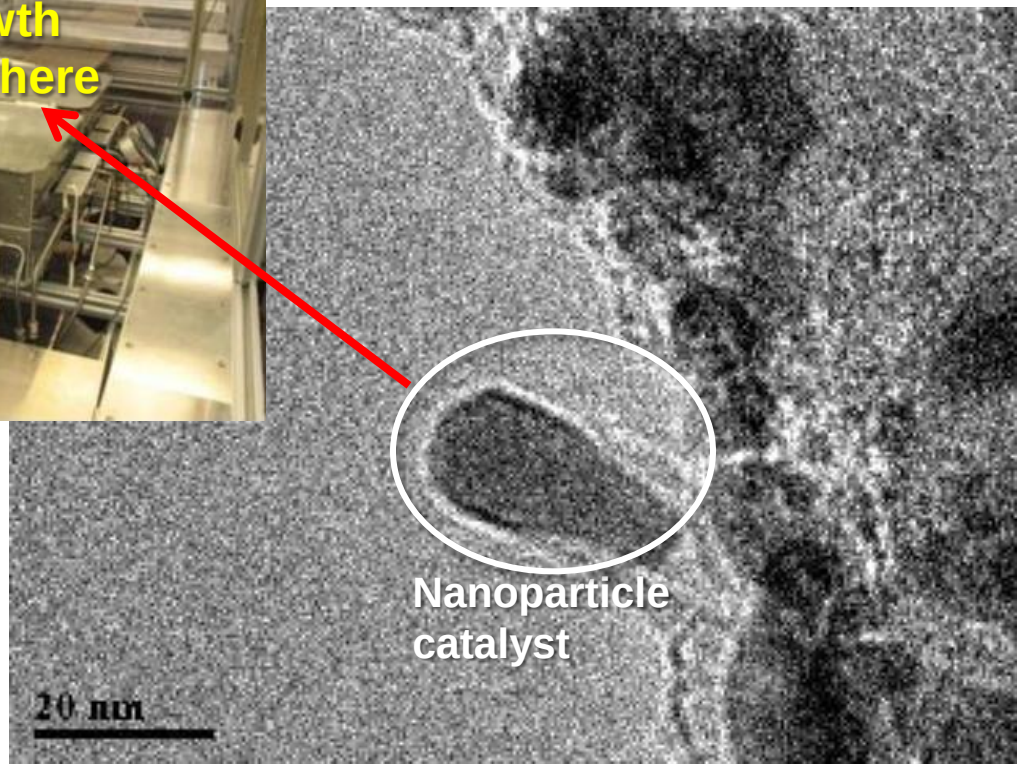
Zammarano et al., ACS Nano, 2011, 5 pp 3391–3399

Process Optimization for CNT Growth

Process optimized here



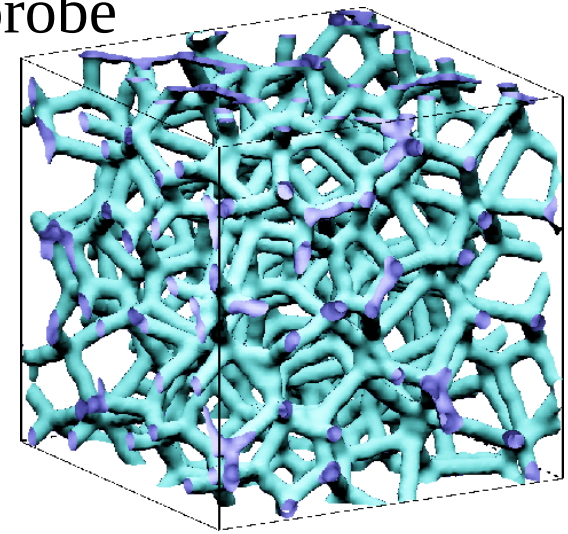
Environmental TEM



- Optimization of CNT growth depends on a detailed understanding of catalyst operation.
- Measurements are needed at the atomic scale under real reaction conditions in real time
- Environmental transmission electron microscopy (ETEM) enables atomic-resolution observation of catalytic processes such as carbon nanotube growth (above).

Modeling

- Connect micro/nanostructure to properties and vice versa to interpret RF/microwave response in terms of structure
  - Need to be faithful to imaging results (2D and 3D)
  - Need to accurately compute 3-D properties of interest – mainly microwave and AC electrical, to connect to QC/QA probe



Model foam – accurately computed elastic moduli and ac/dc electrical conductivity

A.P. Roberts, E.J. Garboczi, Proc. Roy. Soc. Lond. A **458**, 1033-1054 (2002).

External Partners

- Applied Nanostructured Solutions (Lockheed) – pilot line access, prepreg supply, manufacturing input (CRADA in place for CNT growth optimization)
- Nanocomp – pure CNT fiber production
- MIT – composites expertise, custom material fabrication, mechanical testing, aerospace consortium
- NRO – end-user input, R&D & manufacturing
- NASA – CNT R&D expertise, end-user input

Roadmapping exercise underway as part of NSI

Outcomes

- Develop non-contact, high-throughput, in-line metrology for carbon nanocomposite production
  - Innovations
    - Methods of quantifying complex network morphologies
    - Models of composite material electrical response
    - Single-molecule, chemically specific, nanoscale interface/phase imaging techniques
    - *In situ* continuous electrical monitoring of composite material health

Impacts

- New, high-performance, lightweight materials for aerospace, energy and transport
- Rapid deployment of advanced composites
- Lifetime monitoring of structures in service
- Science-based approach to composite design and manufacture

Thank you!

Questions?

CNST: A user facility with a unique design – a resource for nanomanufacturing

- The CNST User Facility: A Nanocenter having a unique, hybrid design:
  - The NanoFab – Provides convenient, shared access to commercial state-of-the-art nanoscale measurement and fabrication tools – *similar in operation to the National Nanofabrication Infrastructure Network (NNIN)*
  - Measurement and Instrumentation Research – Develops cutting edge measurement and fabrication methods that lie beyond the commercial state-of-the-art and are accessible through collaboration – *similar in operation to the DoE Nanocenters*
- *<u>Use</u> the NanoFab*
- *<u>Collaborate</u> with the Measurement and Instrument Researchers!*