Engineering Nanostructures for Thermal Management

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Penn EnerFront Seminar
November 4, 2016

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Heat

- How to control it?
- How to harness it for useful purposes?
- Areas of interest:
  - Thermal energy conversion
  - Thermal management

cdn.wallpapersafari.com/23/83/TZRzHx.jpg

Outline

- Broad overview (~50%)
  - Thermal energy conversion
  - Thermal management
  - Applications and societal implications
  - Why ‘nano’ is different

- My group’s research (~50%)

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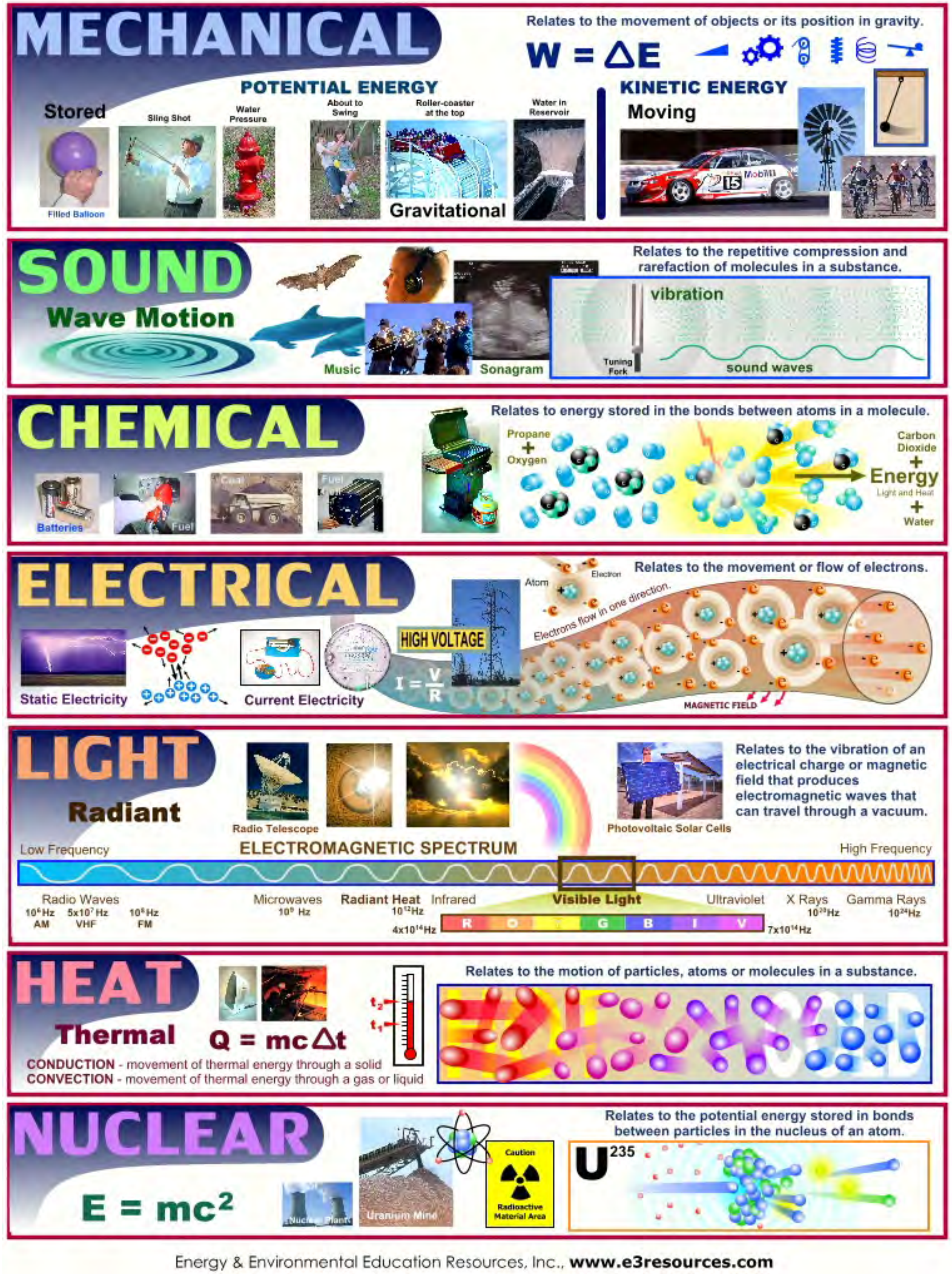
Thermal Energy Conversion

Forms of Energy



Thermal Energy Conversion:

Conversion of heat to a more useful form of energy (often, electricity)

Heat into Electricity

- Two Pathways

1. Indirect energy conversion

   Heat → Mechanical → Electrical

2. Direct energy conversion

   Heat → Electrical

Indirect Energy Conversion

Heat → Mechanical → Electrical

Steam Power Plants

Delaware Generating Station, Philadelphia
www.exeloncorp.com

- Steam power plants provide ~80% of stationary electric power in the U.S.
- Fossil fuels, nuclear fuels, and solar energy provide the heat needed to produce steam from water

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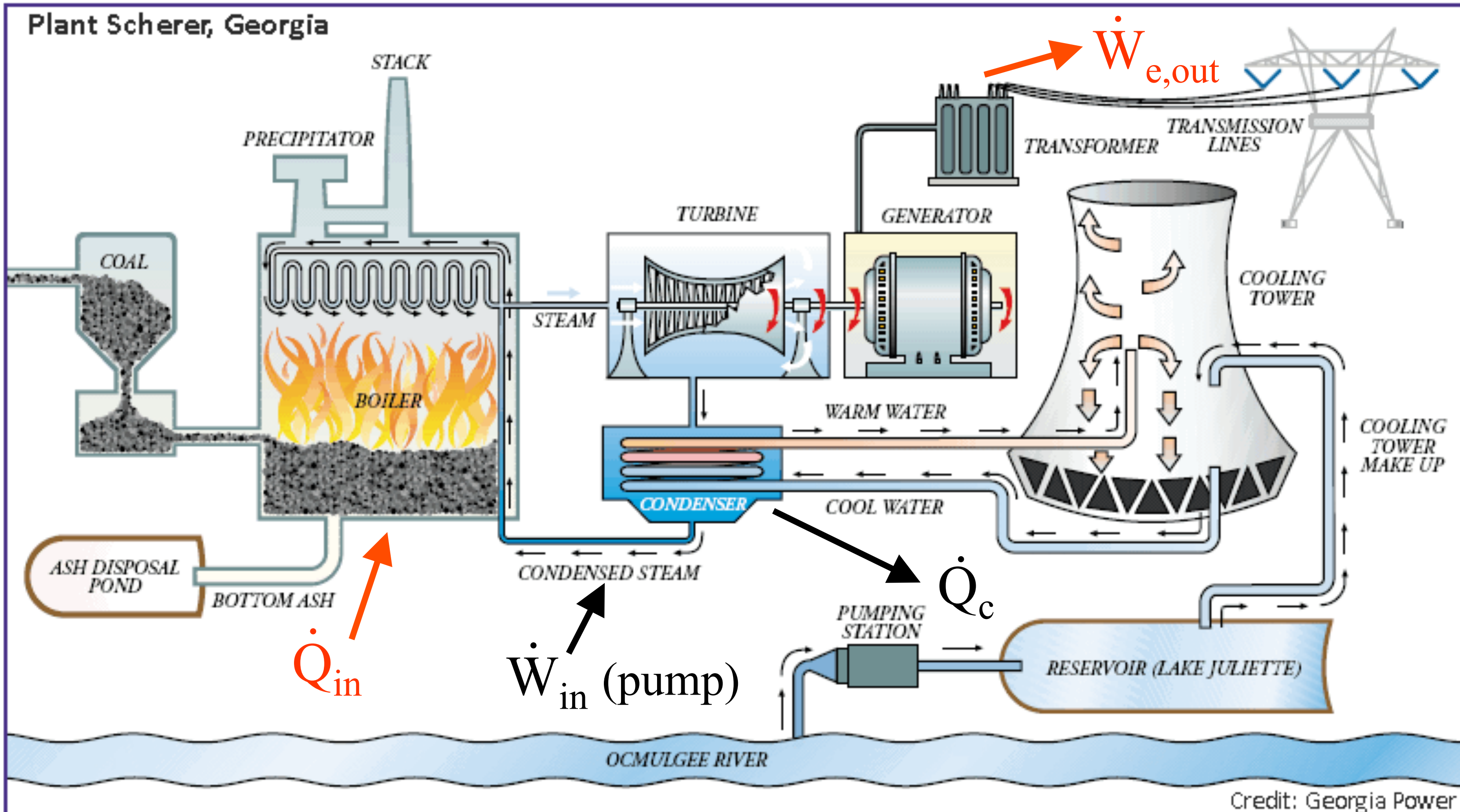
Coal-Fired Steam Power Plant



Put <u>heat</u> in, get <u>electrical power</u> out

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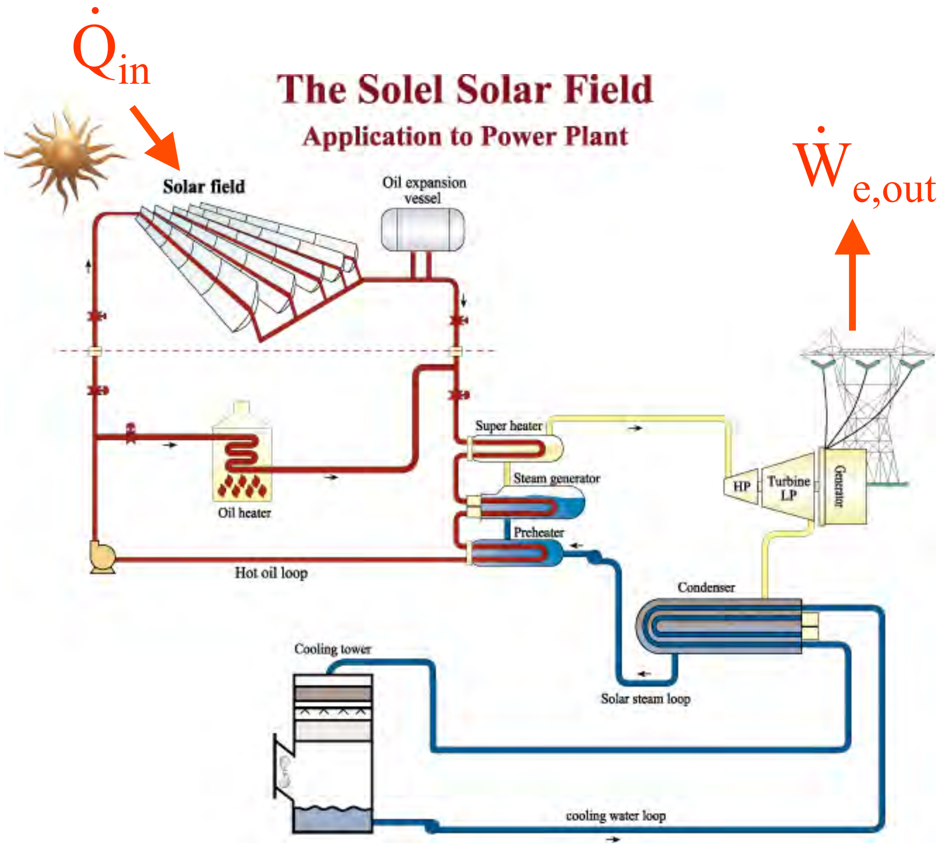
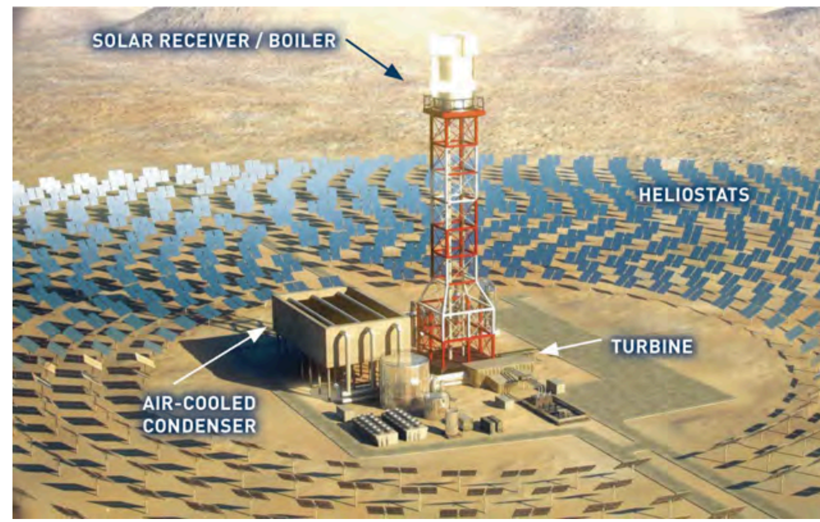
Solar Steam Power Plant



parabolic trough collector

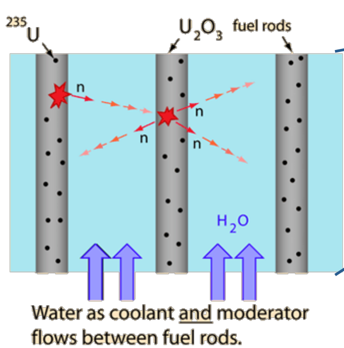


concentrating solar "power tower"
solar-trap.com

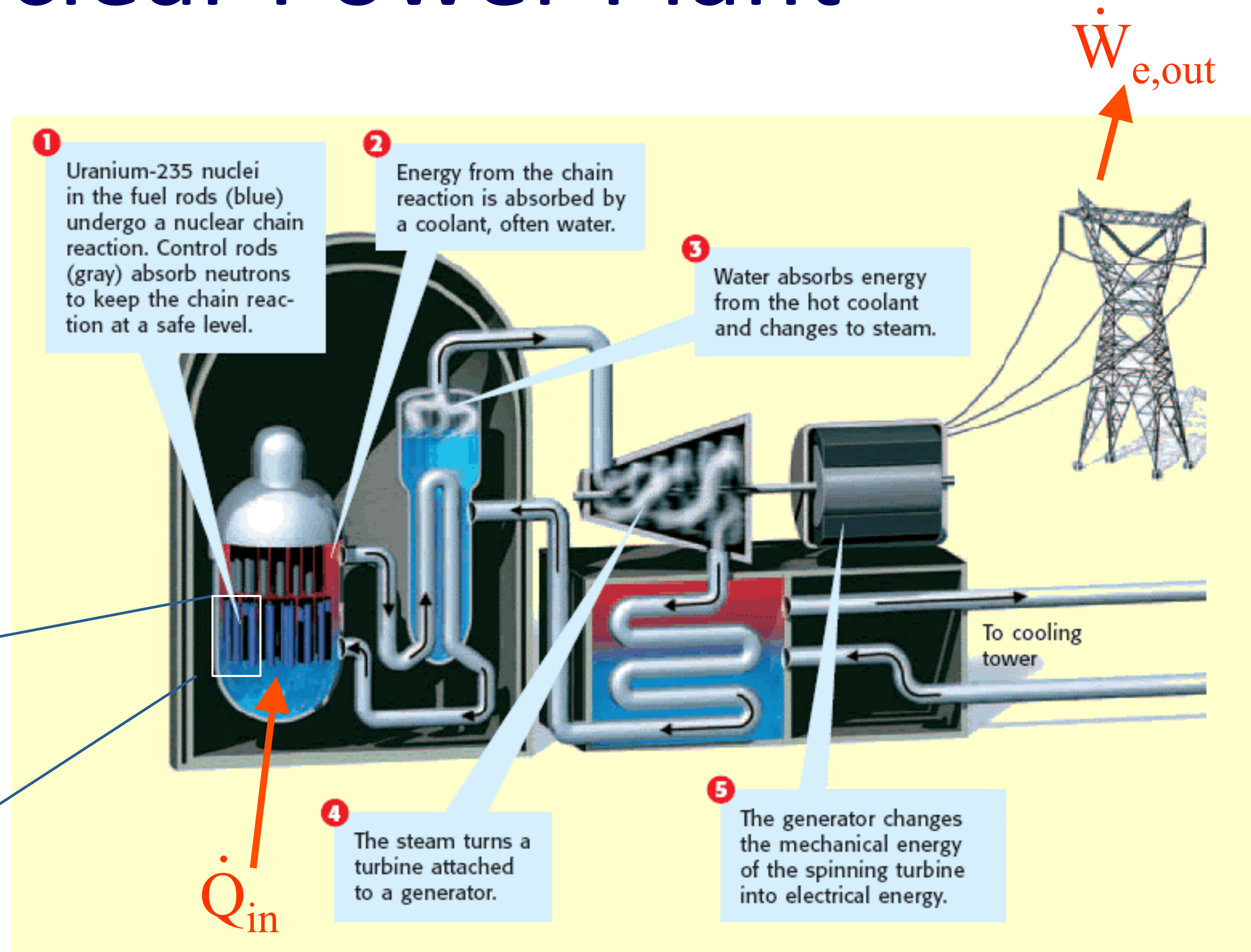
Main difference: heat comes from the sun rather than fossil fuels

Nuclear Power Plant

Three Mile Island



hyperphysics.phy-astr.gsu.edu



edublognss.files.wordpress.com

Main difference: heat comes from nuclear fissions

Engineering

Industrial Waste Heat Recovery

PHOENIX

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Heat Conversion Systems

Phoenix Heat Conversion Systems provide unparalleled return on investments for the reuse of industrial process heat and facilitation of co-generation and tri-generation opportunities. Industrial processes typically require the use of vast quantities of energy, much of which is wasted. Phoenix ORC systems enable the simple and efficient conversion of that waste heat into usable electricity, which can then be either used internally to offset electricity costs, or sold back to the grid to generate revenue. The systems come in various sizes from 10kW to 5MW and greater, and can use a wide variety of either clean or dirty heat sources from 80 degrees C to 900 degrees C.

Reach Us

PHOENIX THERMAL ENERGY CONVERSION

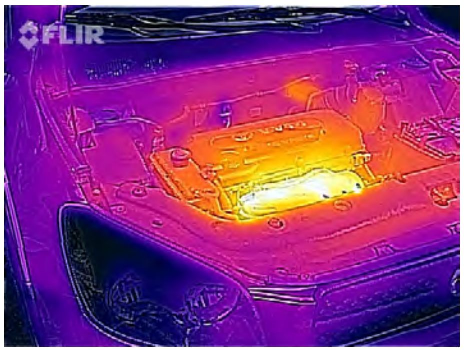
A division of the Fusion Power Systems
www.fusionps.com.au
Head Office
5/4 Rocklea Drive
Port Melbourne VIC 3207
Australia

organic Rankine cycle

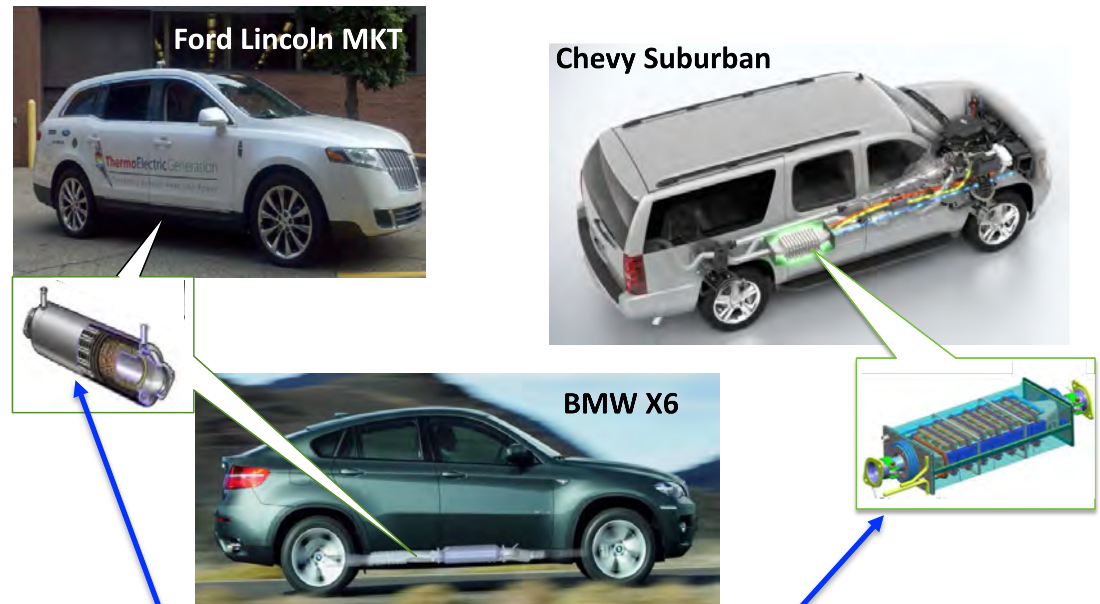
Direct Energy Conversion

Heat → Electrical

Automotive Energy Recovery



Vehicle Integration with Thermoelectics: FORD, GM and BMW
Prototype integration pursued under DOE/industry sponsorship



Fairbanks, 2013

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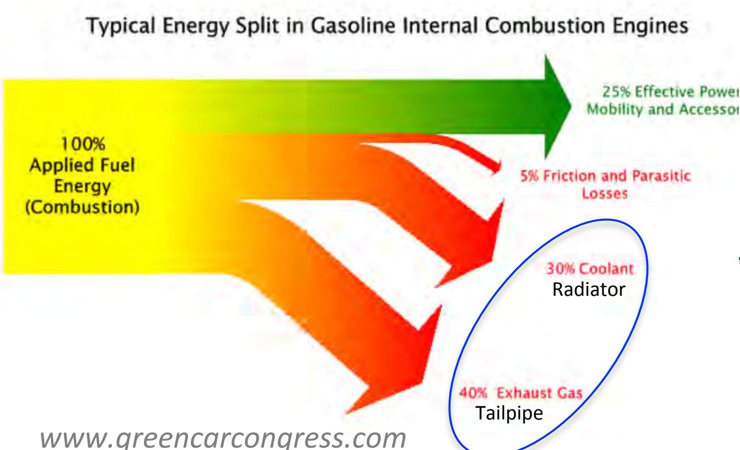
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Thermoelectric generator:
solid-state conversion of heat directly into electricity



www.greencarcongress.com

70% of fuel energy is lost as heat

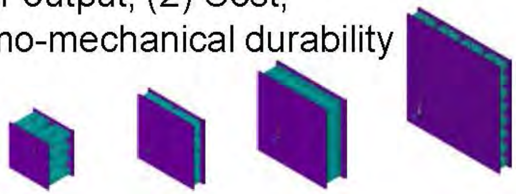
Solid state thermoelectric energy conversion for improved fuel economy

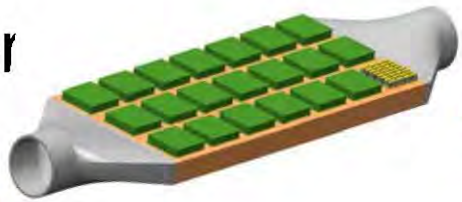
TEG Subsystems Modeling and Design

TE Module Design:

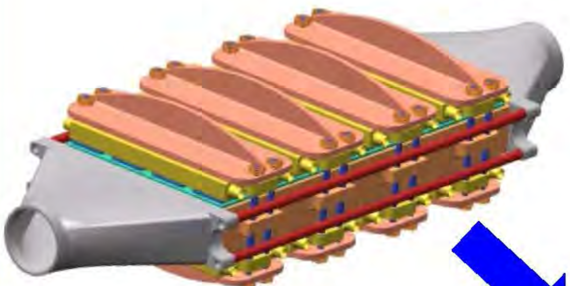
Identify primary module design variables

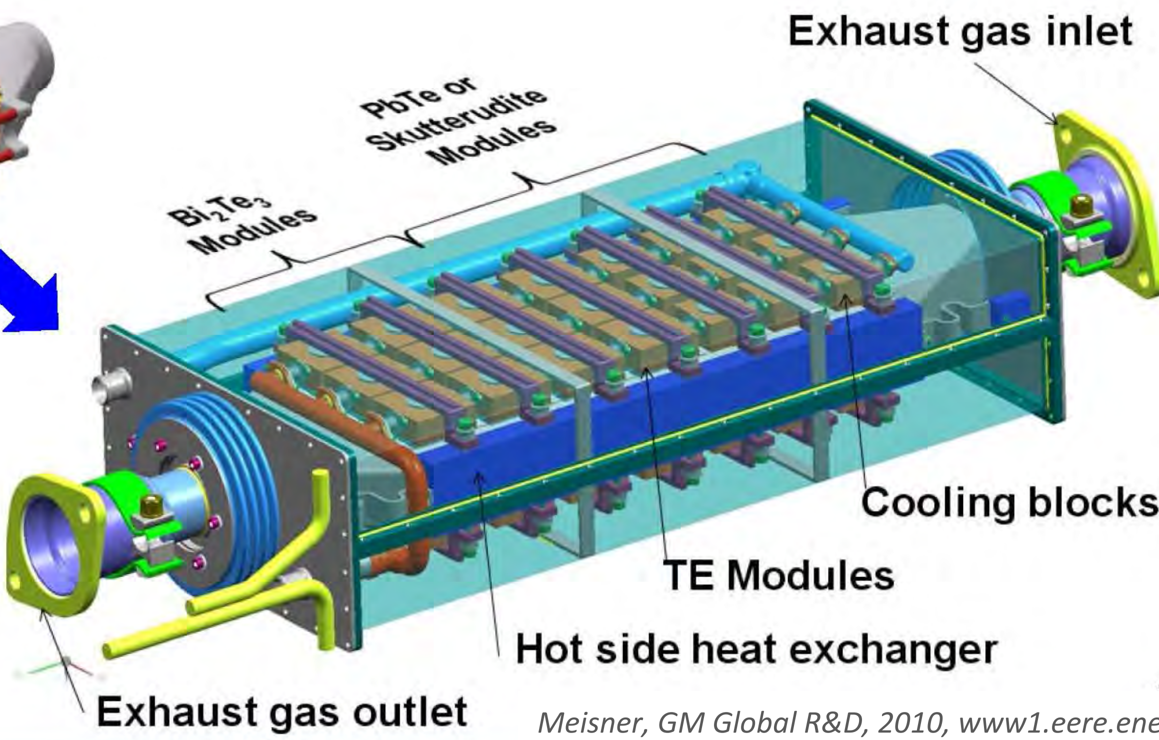
Examine effect on primary output variables:
(1) Power output, (2) Cost,
(3) Thermo-mechanical durability





Heat Exchanger Design:



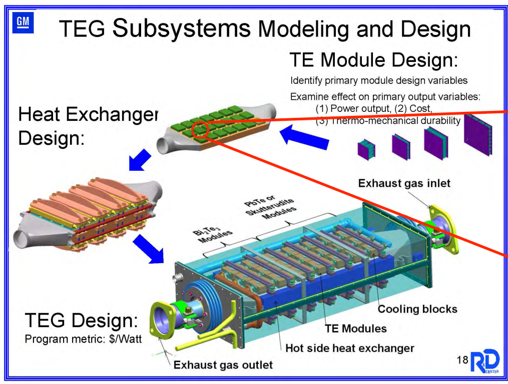


TEG Design:

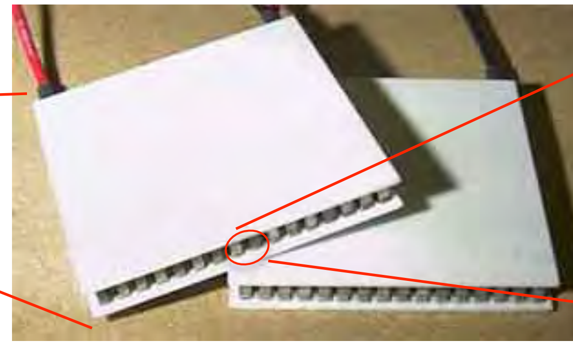
Program metric: $/Watt

Meisner, GM Global R&D, 2010, www1.eere.energy.gov

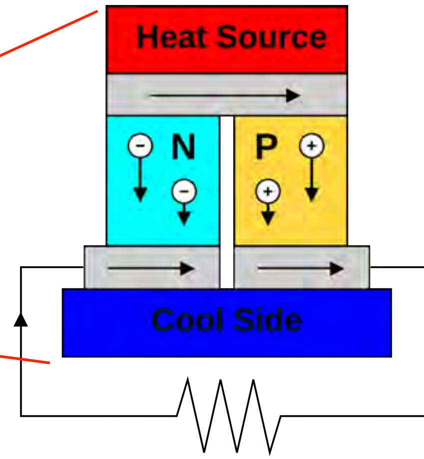
Thermoelectric Module



Meisner, GM Global R&D, 2010, www1.eere.energy.gov



electronickits.com



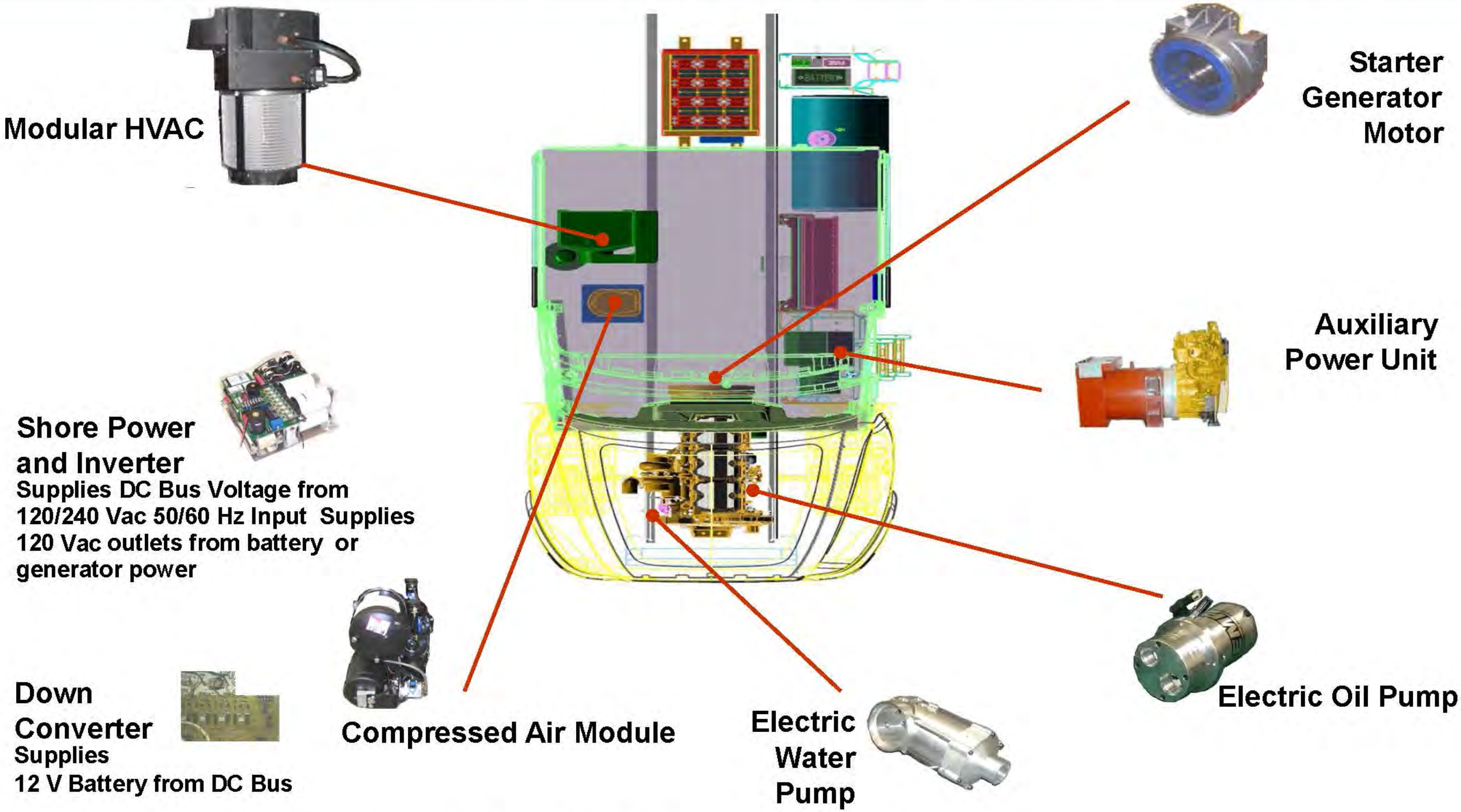
Brazier, Wikimedia Commons

Converts Temperature Difference into Voltage.

How Does it Work?

- Sandwich module between heat source (exhaust pipe) and heat sink (water cooled surface)
- Heating generates electronic carriers in n- and p-type thermoelectric elements
- Carriers drift and diffuse, generating voltage that can be used to power an external load

Fuel economy is improved when belt-driven accessories are replaced with electric motor drives powered by Thermoelectrics



Toward the beltless engine

Fairbanks, 2013

Thermal Management

Managing heat flows to maintain desired temperatures

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Climate

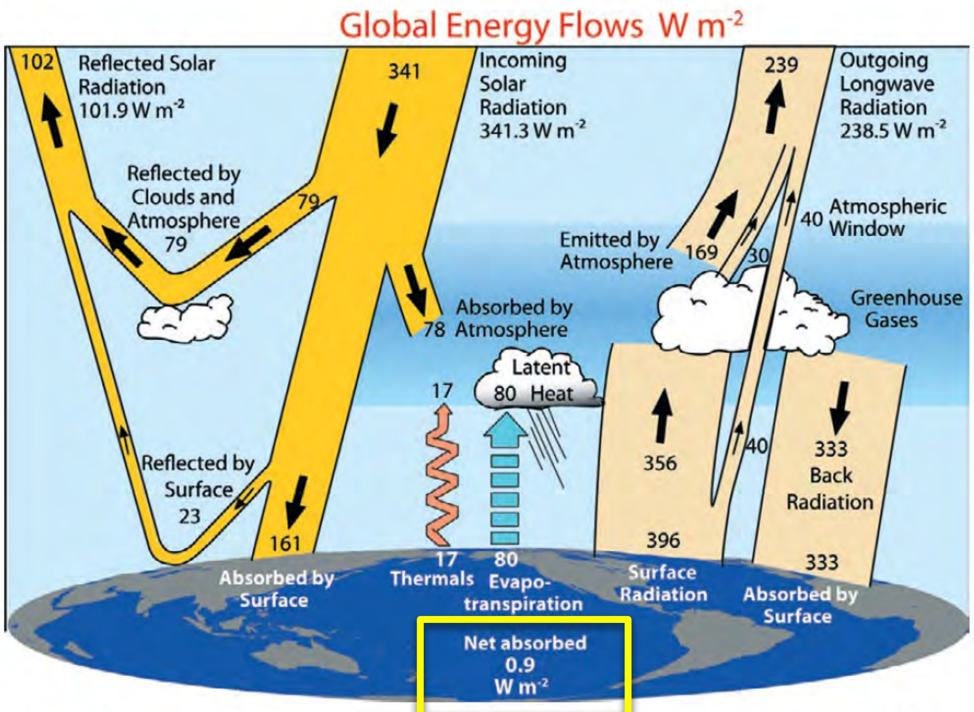
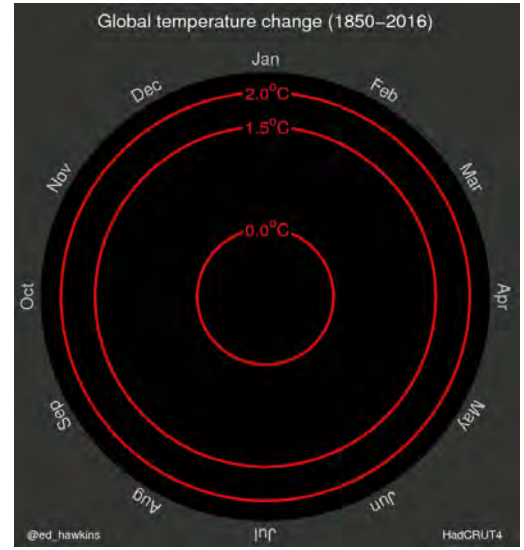
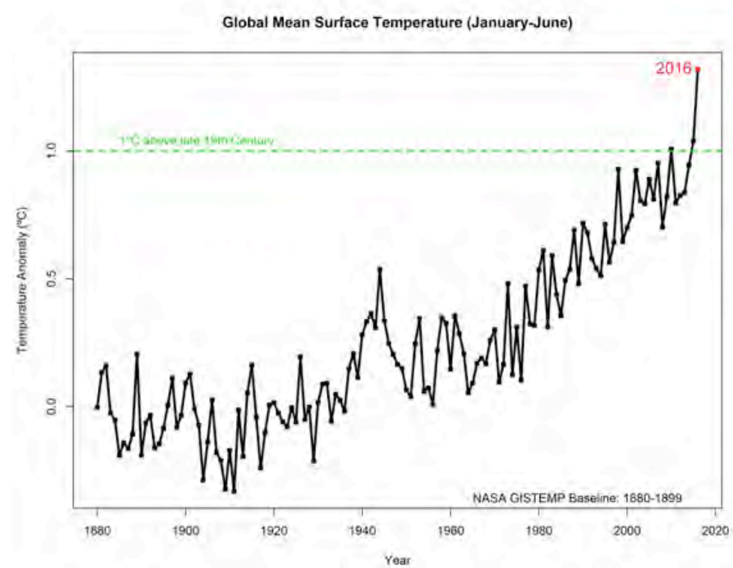


FIG. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period ($W\ m^{-2}$). The broad arrows indicate the schematic flow of energy in proportion to their importance.

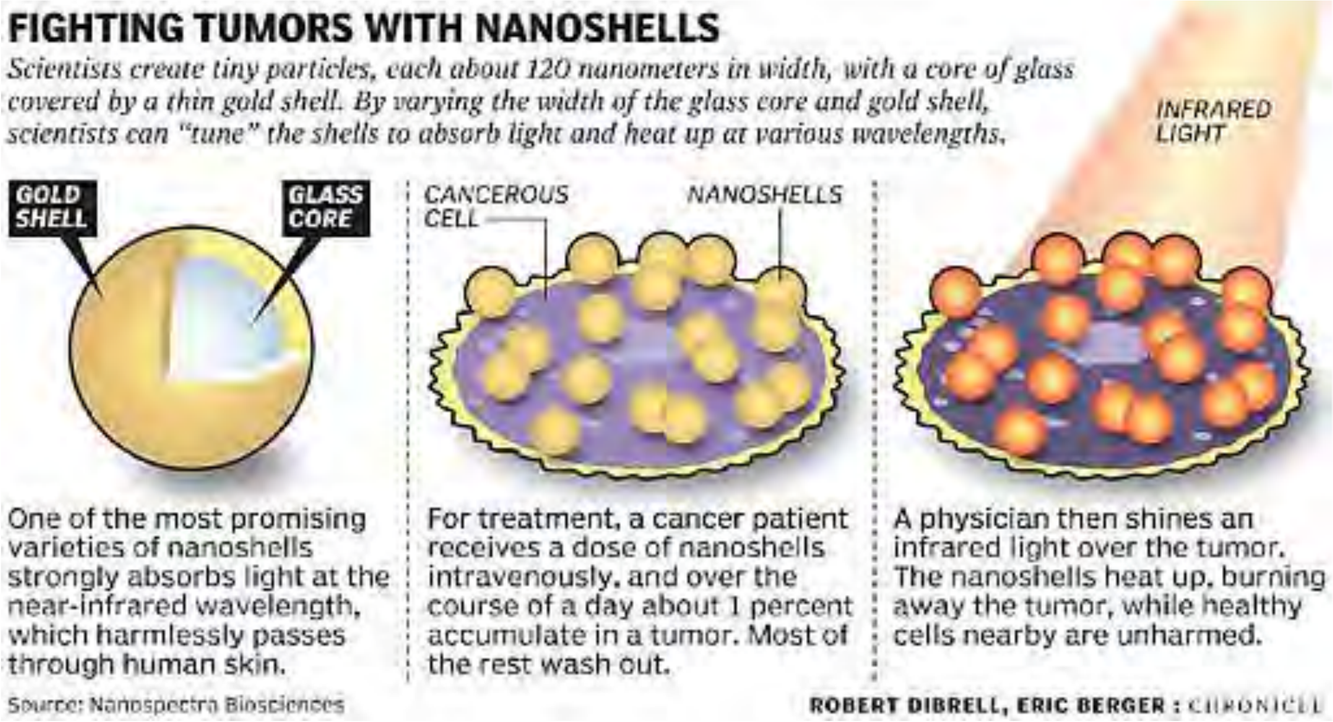
Trenberth et. al, BAMS, 2009





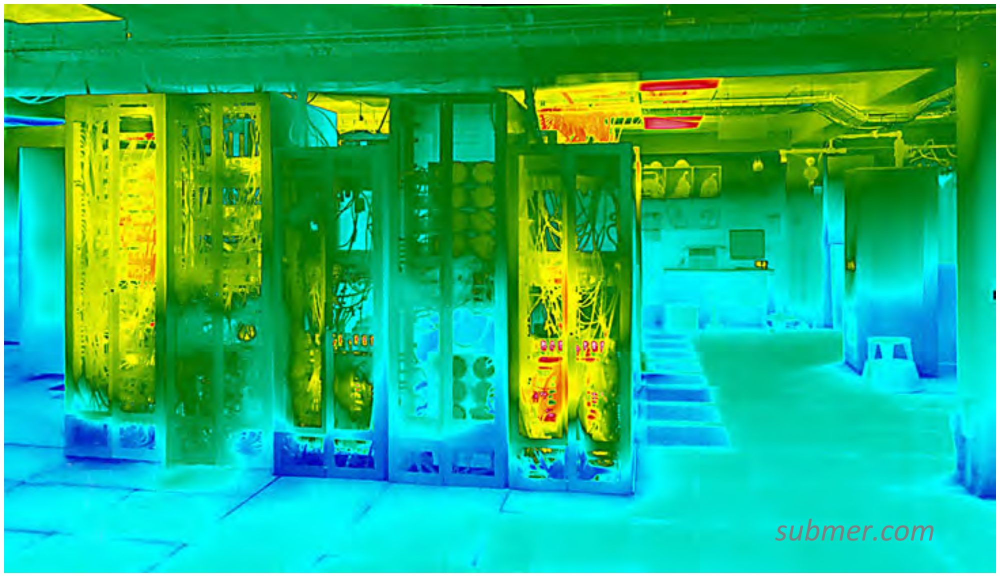
Earth's thermal energy balance

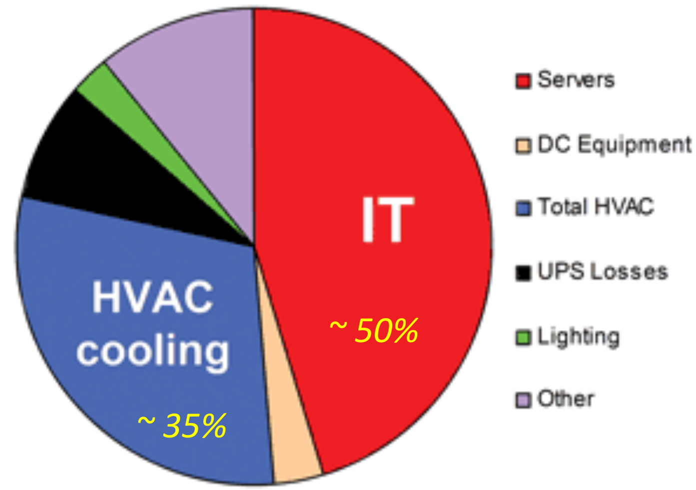
Health



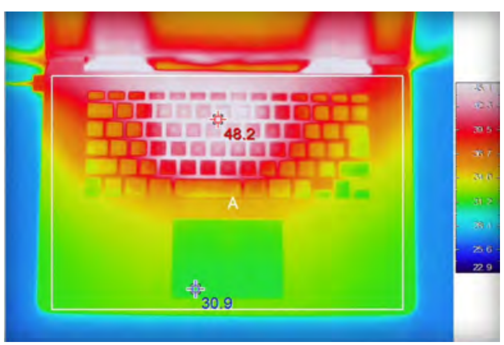
Hyperthermia to treat cancer

Information Technology





Iyengar and Schmidt, 2010, electronics-cooling.com



www.sciencealert.com

Cooling: a significant fraction of data center operating costs

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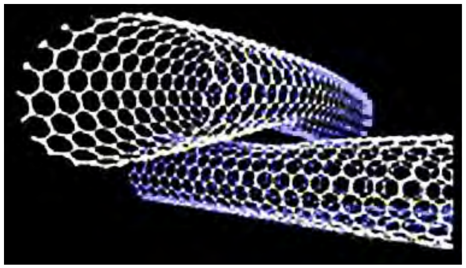
Lukes Group Research

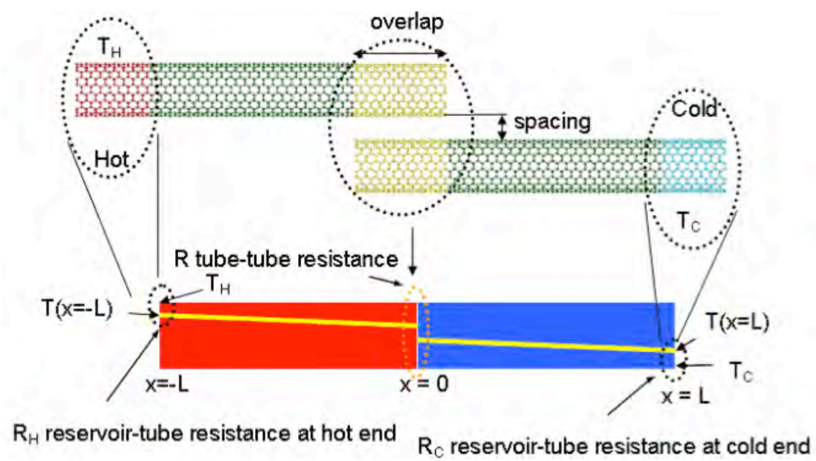
Overall Goal 1

Engineer the nanoscale structure of materials and interfaces to obtain desired thermal properties

Carbon Nanotube-Based Materials



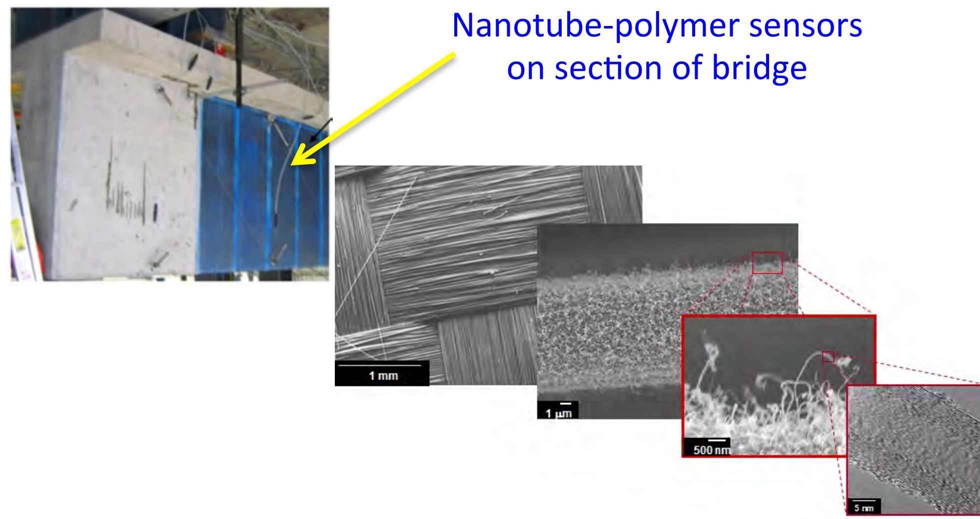
Nanotube-nanotube interface
www.staff.uni-mainz.de/banhart



Thermal transport across nanotube-nanotube interface
Zhong and Lukes, PRB, 2006

Electrically conductive nanotube-polymer networks for structural health monitoring
sites.udel.edu/nsf-cmmi-cnt-shm

Nanotube-polymer sensors on section of bridge



Hierarchical view of sensor structure

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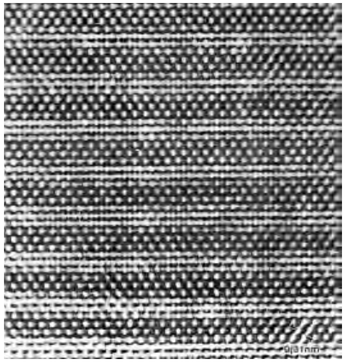
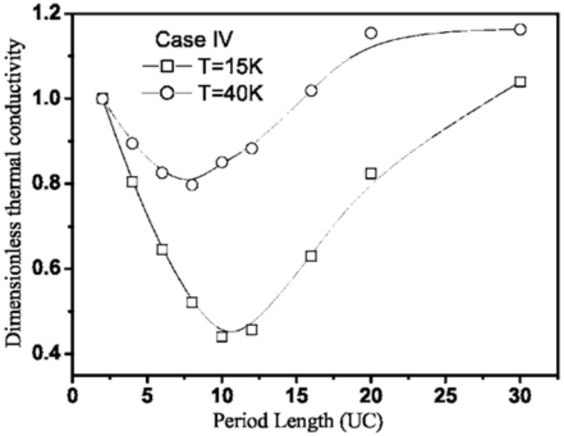
Superlattice-Based Materials



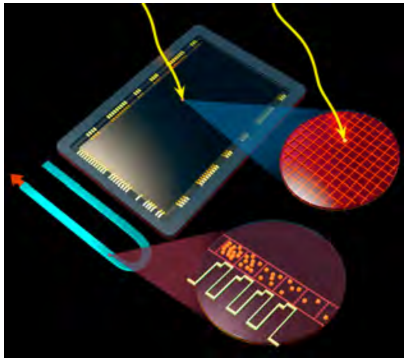
Superlattice atomic structure
www.tf.uni-kiel.de/matwis/ama

Enhanced ultraviolet light detectors for space applications

Hubble Space Telescope floating over Earth
NASA, 2009



Minimum superlattice thermal conductivity
Chen et al., PRB, 2005

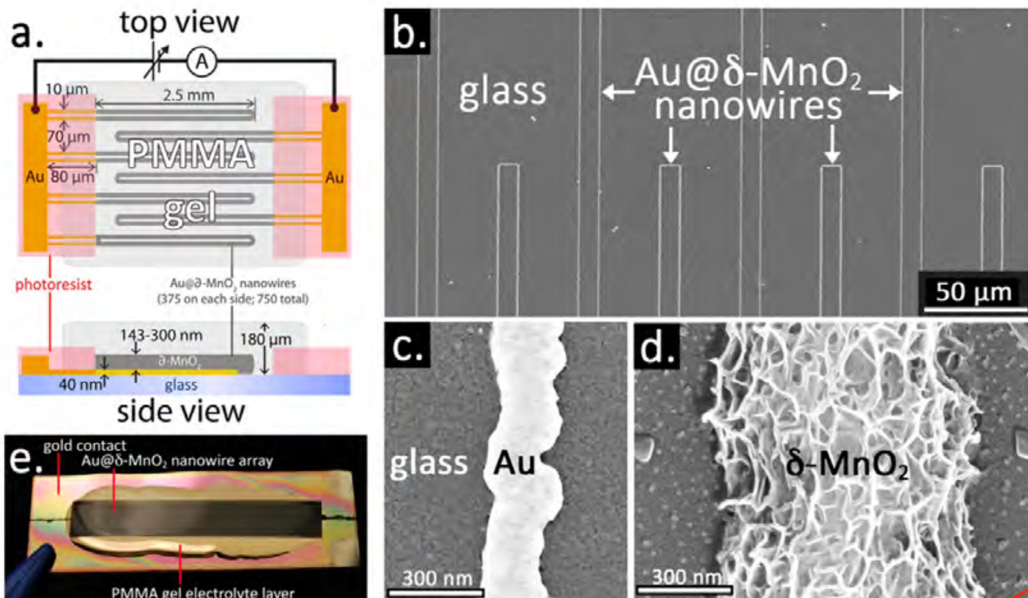


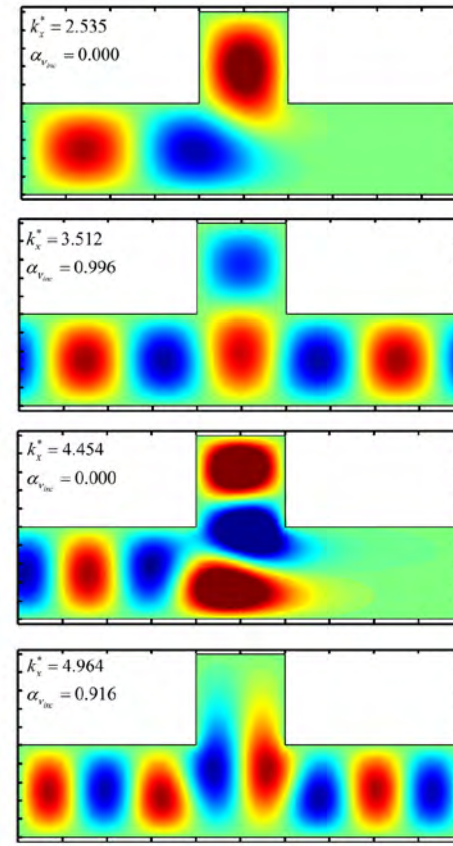
Electron multiplying charge coupled device
NASA, 2009

Nanowire Arrays

Flexible, stable nanowire batteries

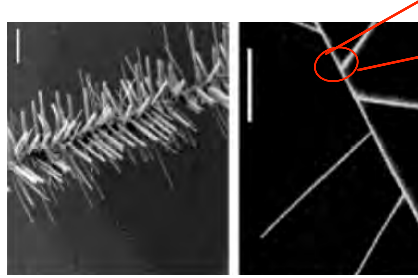
Thai et al., ACS Energy Letters, 2016





Controlling transport of phonons by tuning nanostructure

Cheney and Lukes, JHT, 2013

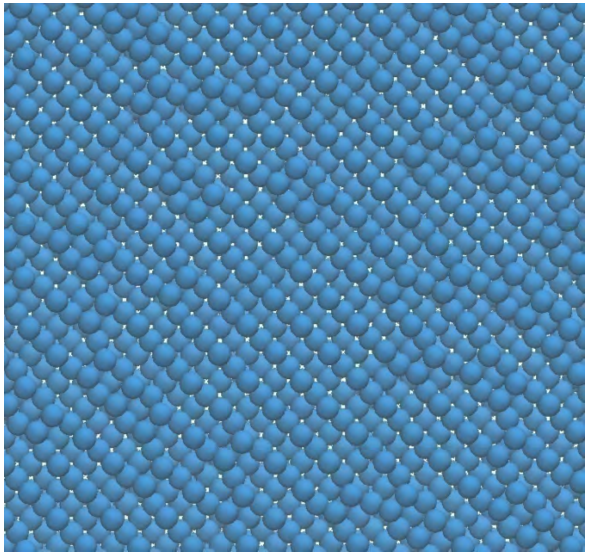


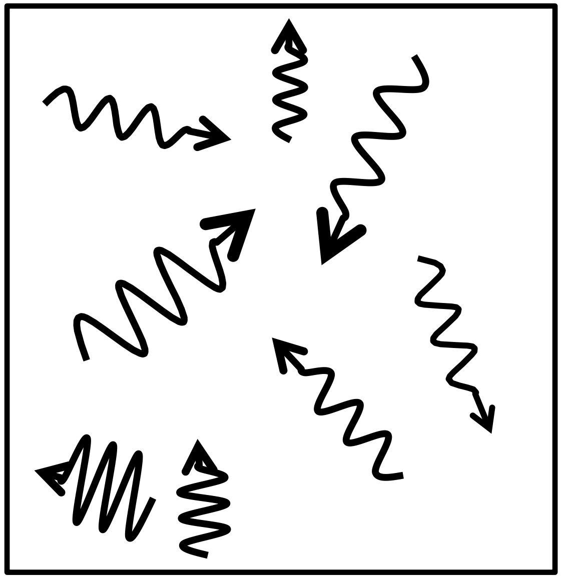
Branched nanowires

Wang et al., Nano Lett., 2004

What is a Phonon?

Thermal vibration of atoms in a material



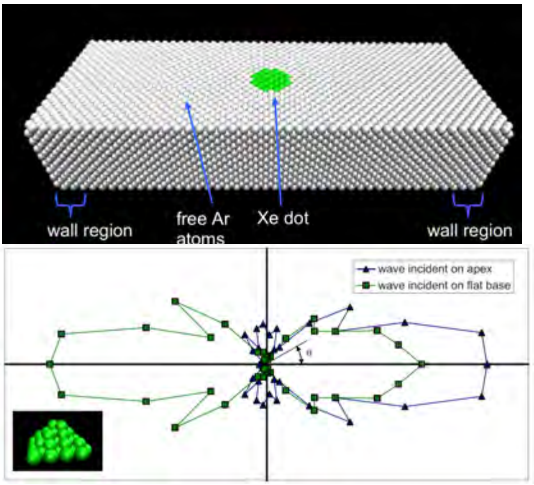


- Many different vibrational modes
- Travel in all directions
- Scatter off of each other, boundaries and material impurities

Overall Goal 2

Understand fundamental transport processes relevant to thermal management and thermal energy conversion

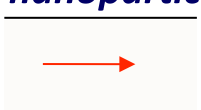
Where Do Phonons Go After Scattering from Nanoparticles?



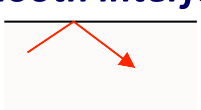
Phonon scattering from embedded nanoparticles
Zuckerman and Lukes, PRB 2008

NO BACKSCATTERING
Higher conductivity

no nanoparticles

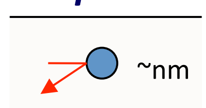


smooth interface

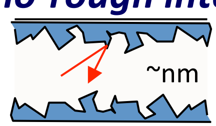


BACKSCATTERING
Lower conductivity

nanoparticles



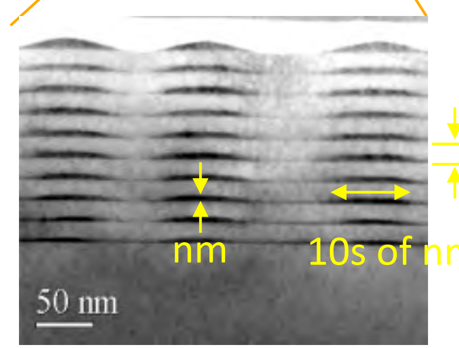
nano-rough interface



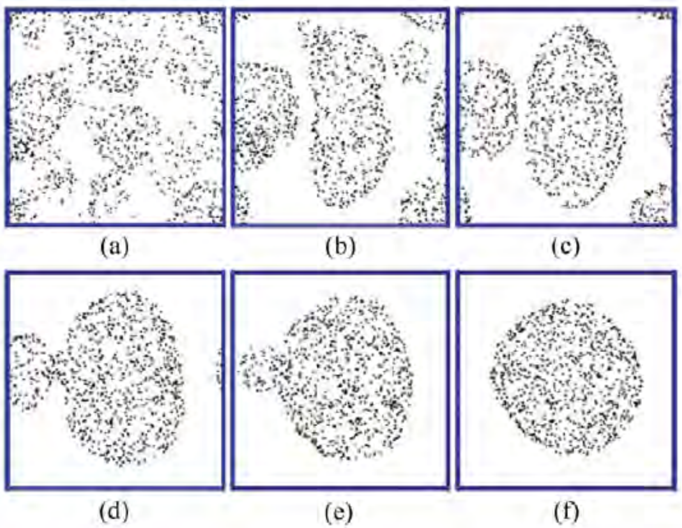
Reducing thermal conductivity using nanostructures

Thermoelectric module
electronickits.com

Silicon/germanium quantum dot superlattice
web.chemistrymag.org

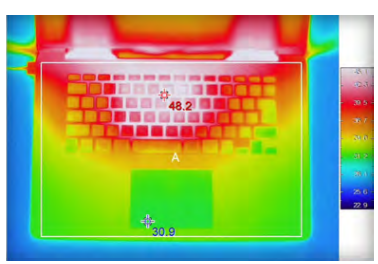


How do Bubbles Form at Nanotextured Interfaces?



Nucleation and coalescence of vapor bubbles

Cosden and Lukes, JHT 2011

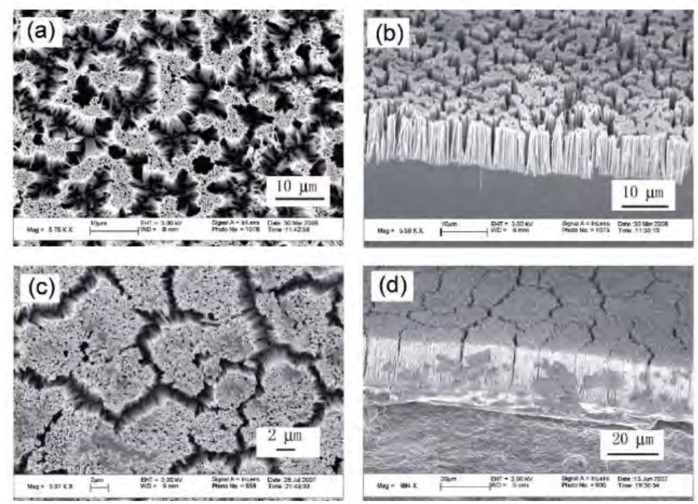


www.sciencealert.com

100% enhancement in cooling performance with nanowire coated surfaces

Si NWs →

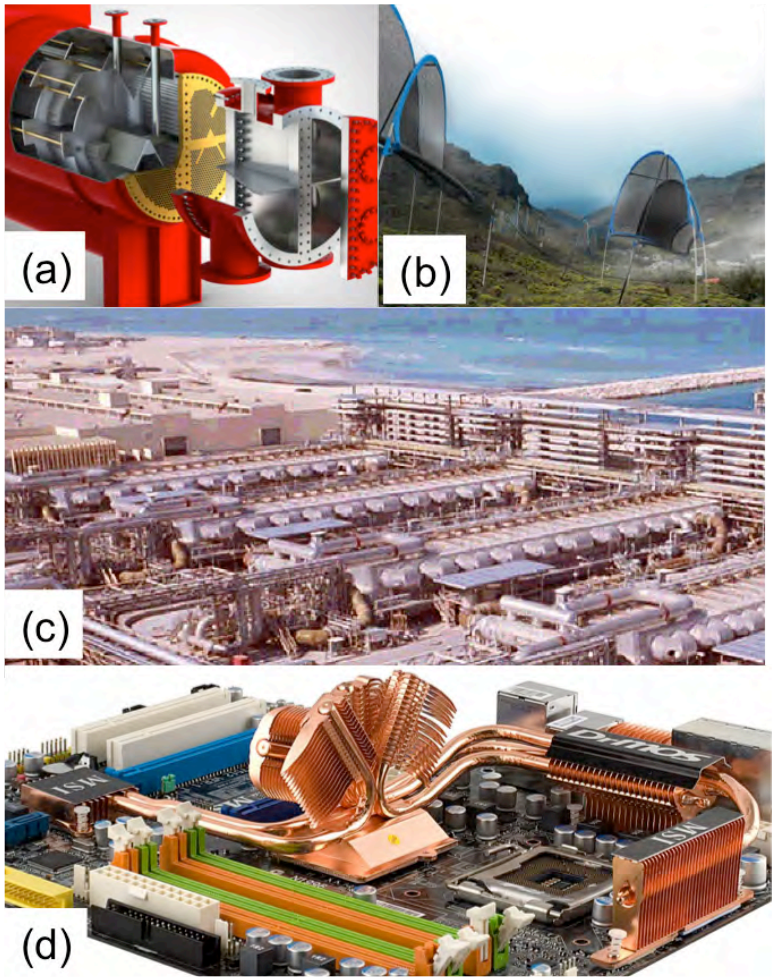
Cu NWs →



Nanowire coated surfaces

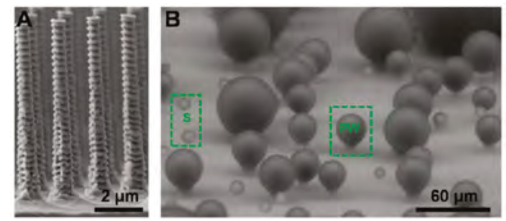
Chen et al. Nano Lett., 2009

How do Droplets Form at Nanotextured Interfaces?



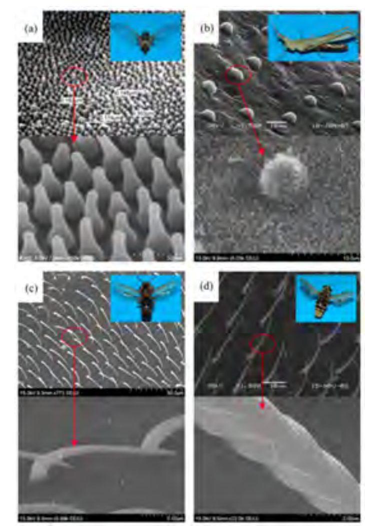
(a) Steam condenser. (b) Fog harvesters.
(c) Thermal desalination plant. (d) Heat pipe.

Enhanced ability to condense steam and collect clean water



Droplet condensation on silicon nanopillars
Miljkovic et al., ACS Nano, 2012

Hierarchical micro/nano structures on insect wings
Byun et al., JBE, 2009

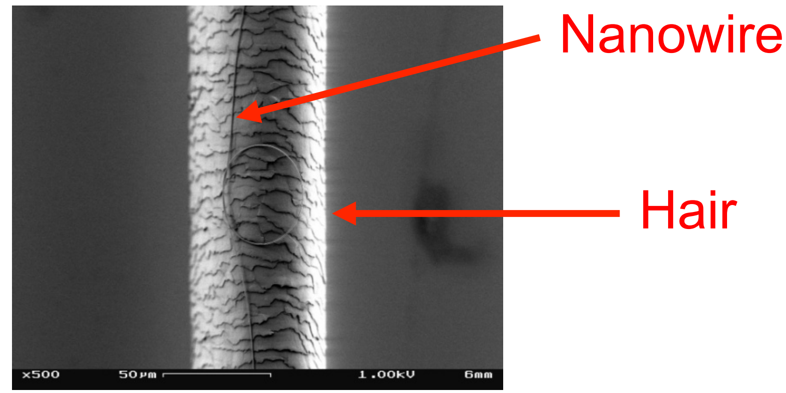


Research Methodology

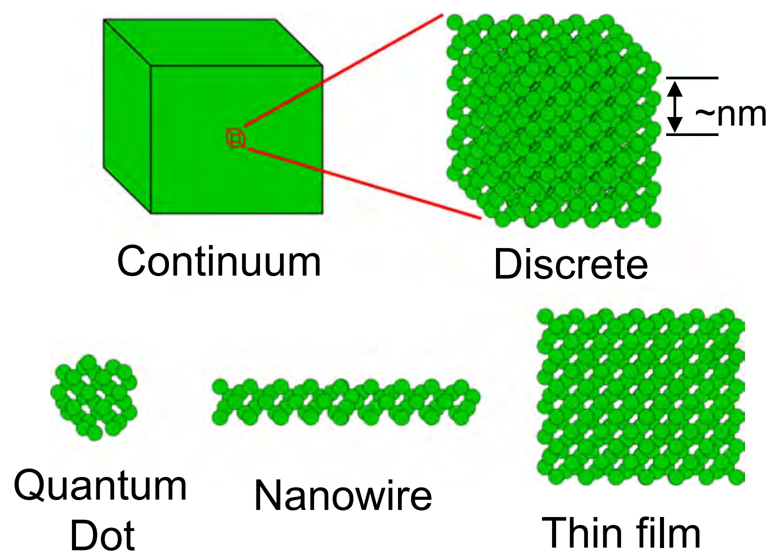
Primarily theoretical modeling at atomic, nano-, micro-, and macroscopic scales

What is Different about "Nano" ?

- Nanometer:
  - 1 billionth of a meter
  - ~50,000 times smaller than a human hair
- Nanometer-scale structures
  - Continuum description questionable
  - Atomic granularity apparent
  - ➢ **Small size → departures from 'textbook' physical properties**



www.nsf.gov. Credit: Limin Tong/Harvard

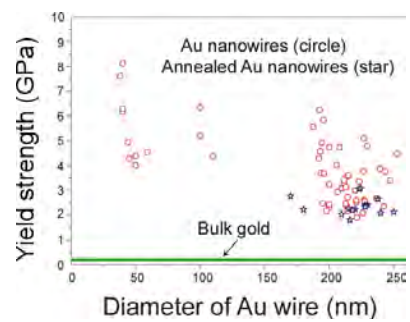


Size-Dependent Physical Properties

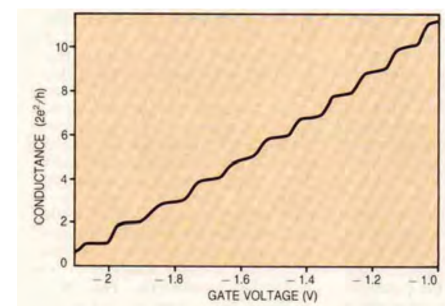
- **Optical**
  - Size selectivity of emitted light color

Increasing quantum dot size →

- **Mechanical**
  - Diameter-dependent yield strength of Au nanowires[1]

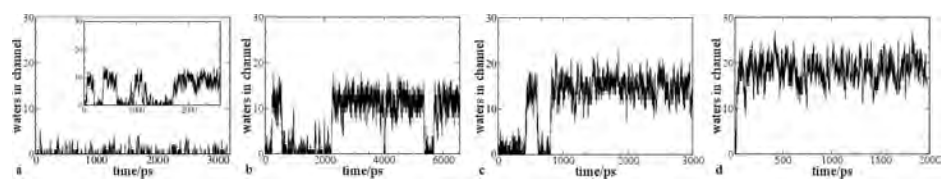


- **Electronic**
  - Quantized conductance in channels[2]



➢ **Thermal**
  - Low nanowire and high nanotube conductivity

- **Fluidic**
  - Increased viscosity
  - Intermittent nanopore permeation by water[3]



Increasing pore size →

[1]*Wu, Heidelberg, Boland, Nature Materials 4, 525, 2005*
[2]*Khurana, Physics Today, 21, Nov. 1988*
[3]*Allen, Melchionna, Hansen, PRL 89, 175502, 2002*

J. R. Lukes

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Our Research

Increase efficiency of thermal to electric energy conversion

automotive and industrial energy harvesting

- **Reduce thermal conductivity with nanostructured materials**
- **Understand mechanisms of thermal-magnetic coupling**

Enhance condenser performance

higher efficiency power plants, more effective cooling, water harvesting, desalination

- **Increase rates of liquid droplet nucleation and removal using nanostructured condenser surfaces**

Namib desert beetle
www.theaustralian.com.au

Control direction of heat flow

better thermal management

- **Tailor nanostructure of thin films to control heat transmission**

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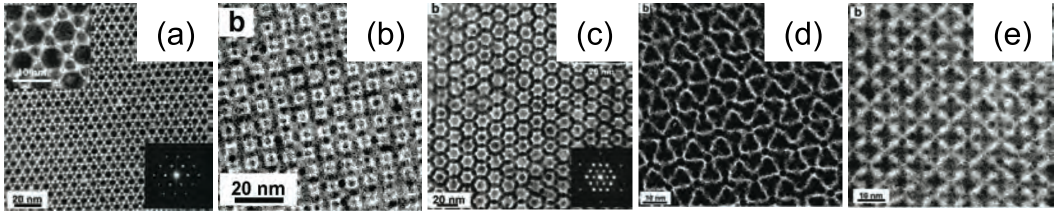
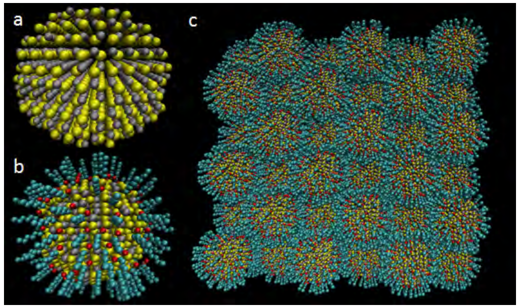
Nanocrystal Superlattice Thermal Conductivity

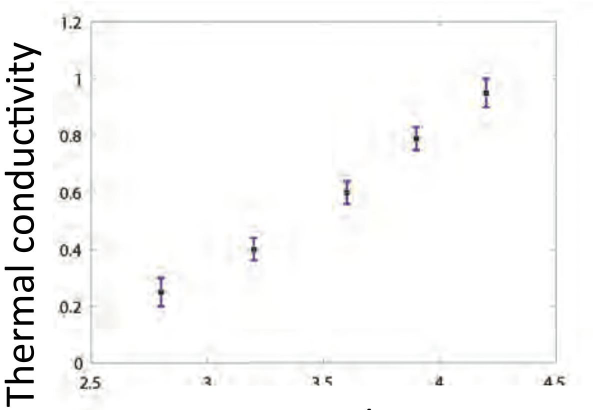
Dr. Mehdi Zanjani



Binary NSL (Shevchenko, Talapin, Murray , O'Brien, JACS 2006)



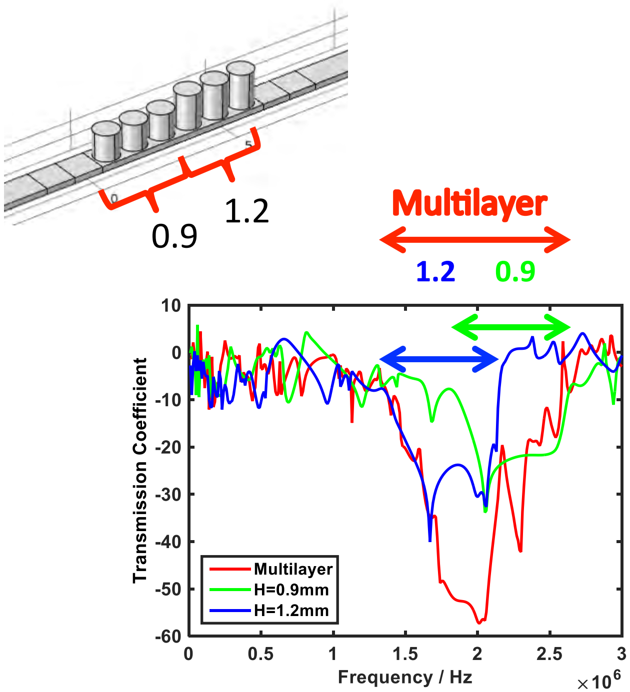
Computer model of CdSe NSL

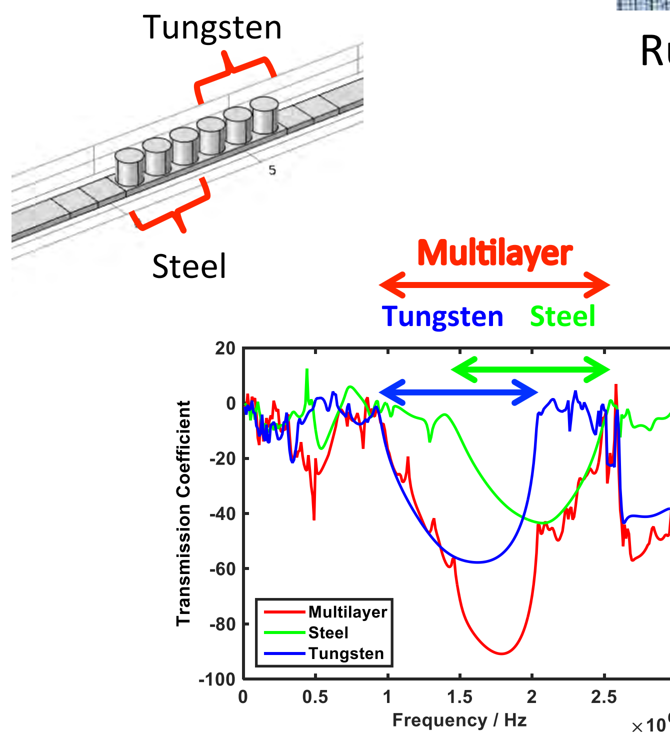


- Vast range of NSL structures
- Thermal conductivity of NCSL increases with size of nanocrystal core
- Tunable structures → "materials by design" for thermal applications
- Atomistic modeling needed to properly capture correct material properties

Multilayer Phononic Crystals to Reduce Heat Transmission

Ruiyuan Ma

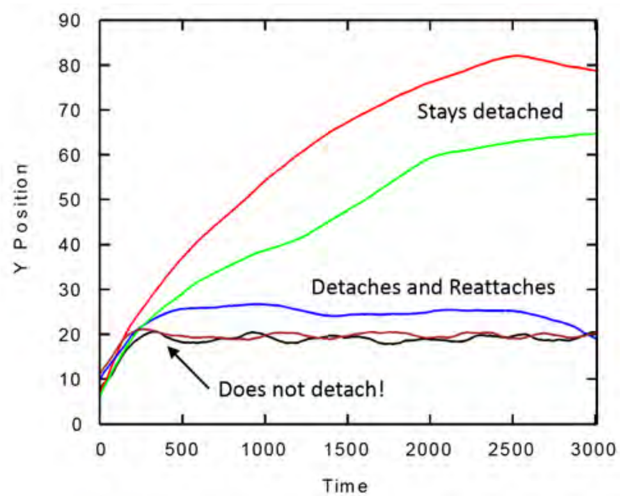




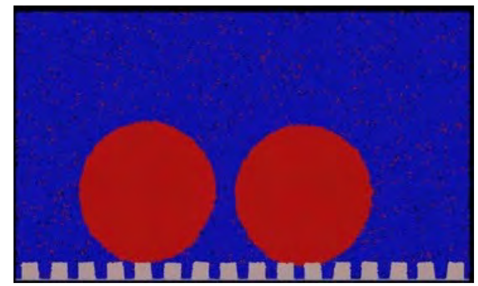
- Band gaps in multilayer structures are larger than those of uniform materials
- Wider band gaps → reduced heat transmission
- Shape, size, spacing, and composition can be used to tune the band gap

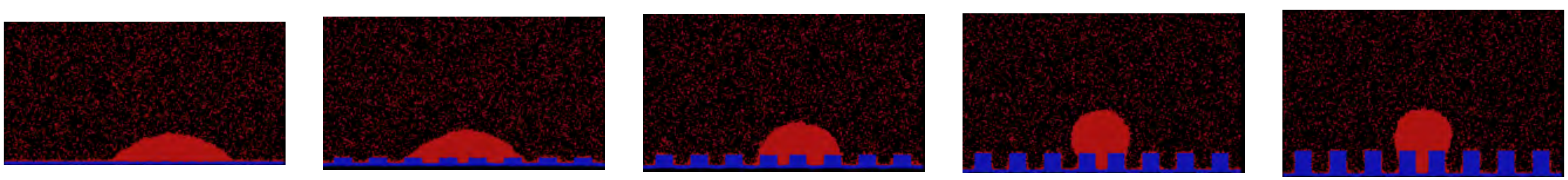
Droplet Jumping from Nanostructured Surfaces

Paul Barclay



Smooth Black
$p_H \approx 4.27$
$p_H \approx 8.55$
$p_H \approx 12.82$
$p_H \approx 17.10$

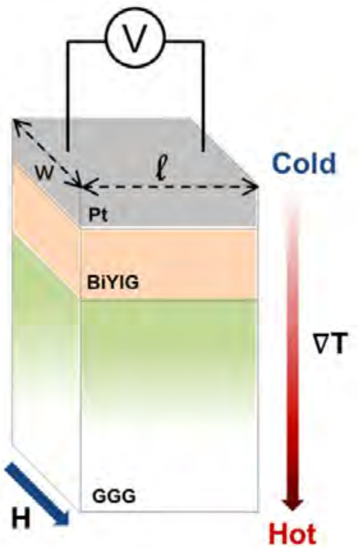




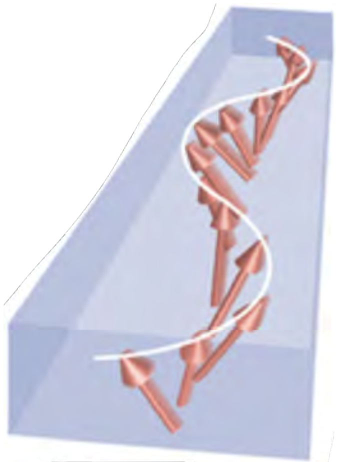
- Geometry of surface determines whether and how high droplets jump
- Jumping → better heat removal from condenser surface
- Higher pillars are not always better

Thermal to Electric Energy Conversion in Magnetic Insulators

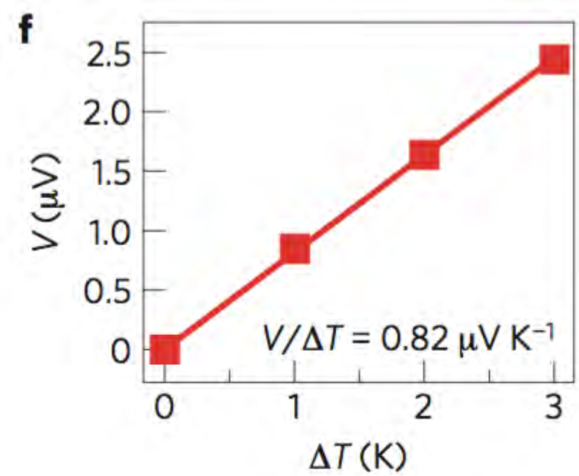
Joe Cooke



Longitudinal Spin Seebeck Effect
Siegel et al., Sci. Rep. 2014



Spin Wave
Kajiwara et. al, Nature, 2010

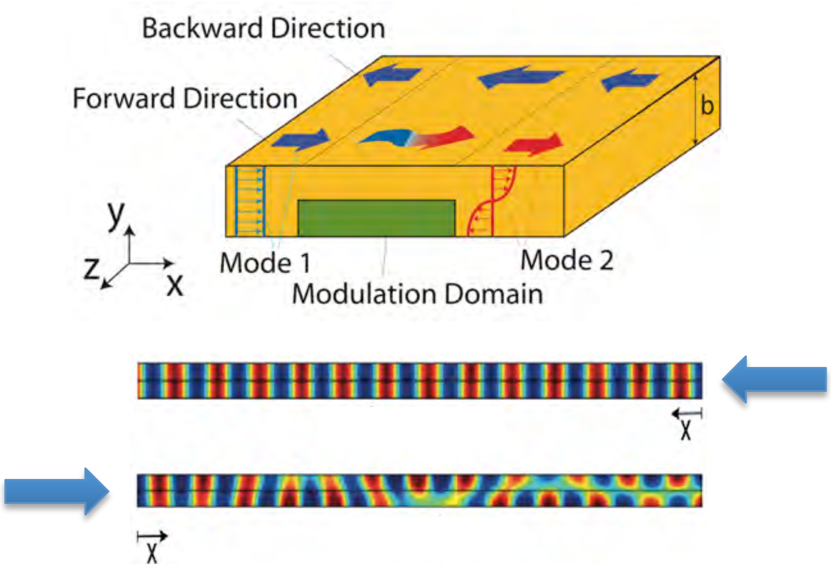


LSSE Voltage
Kirihara et al., Sci. Rep. 2012

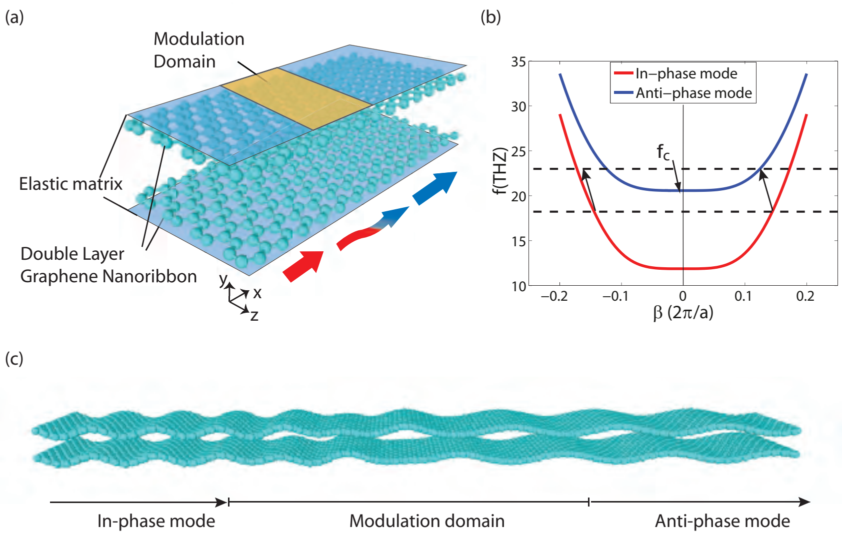
- Temperature gradient across magnetic layer drives a spin current
- Spin current creates voltage in the metallic layer (V proportional to ΔT)
- Currently developing models to capture thermal-magnetic coupling

One-Way Phonon Transport

Collaboration with Engheta group



color: out-of-plane displacement



- Applied spatio-temporal modulation to solid and double layer graphene nanoribbon waveguides
- Observed one-way transport of the mode in the leftward direction only
- Potential to route heat in desired directions

Summary

- The structure of materials and interfaces can be engineered at the nanoscale to yield unusual thermal transport properties

- This can lead to new capabilities for thermal energy conversion and thermal management

- Impacts
  - Automotive fuel economy
  - Clean water production
  - Nuclear, coal, and solar power plants
  - Human health
  - Earth's climate
  - Electronic system reliability

Acknowledgments