

# Engineering Nanostructures for Thermal Management

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*Penn EnerFront Seminar  
November 4, 2016*



# Heat

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

# Outline

- **Broad overview** (~50%)
  - Thermal energy conversion
  - Thermal management
  - Applications and societal implications
  - Why 'nano' is different
- **My group's research** (~50%)

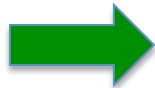
# Thermal Energy Conversion



# Forms of Energy

## Thermal Energy Conversion:

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



**MECHANICAL**  $W = \Delta E$  Relates to the movement of objects or its position in gravity.

**POTENTIAL ENERGY**

Stored: Filled Balloon, Sling Shot, Water Pressure, About to Swing, Roller-coaster at the top, Water in Reservoir

**KINETIC ENERGY**

Moving: Gravitational, Car, Windmill, Bicycles

**SOUND** **Wave Motion** Relates to the repetitive compression and rarefaction of molecules in a substance.

Music, Sonagram, vibration, sound waves

**CHEMICAL** Relates to energy stored in the bonds between atoms in a molecule.

Batteries, Fuel, Coal, Propane + Oxygen, Carbon Dioxide + Energy + Light and Heat + Water

**ELECTRICAL** Relates to the movement or flow of electrons.

Static Electricity, Current Electricity, HIGH VOLTAGE,  $I = \frac{V}{R}$ , Atom, Electron, Electrons flow in one direction, MAGNETIC FIELD

**LIGHT** **Radiant** Relates to the vibration of an electrical charge or magnetic field that produces electromagnetic waves that can travel through a vacuum.

Radio Telescope, Photovoltaic Solar Cells

**ELECTROMAGNETIC SPECTRUM**

Low Frequency: Radio Waves (10<sup>4</sup> Hz, 5x10<sup>7</sup> Hz, 10<sup>10</sup> Hz), AM, VHF, FM

Microwaves (10<sup>9</sup> Hz)

Radiant Heat (10<sup>12</sup> Hz, 4x10<sup>14</sup> Hz)

Infrared

**Visible Light** (R, O, Y, G, B, I, V)

Ultraviolet (7x10<sup>14</sup> Hz)

X Rays (10<sup>18</sup> Hz)

Gamma Rays (10<sup>24</sup> Hz)

**HEAT** **Thermal**  $Q = mc\Delta t$  Relates to the motion of particles, atoms or molecules in a substance.

CONDUCTION - movement of thermal energy through a solid

CONVECTION - movement of thermal energy through a gas or liquid

**NUCLEAR**  $E = mc^2$  Relates to the potential energy stored in bonds between particles in the nucleus of an atom.

U<sup>235</sup>, Caution, Radioactive Material Area

# 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

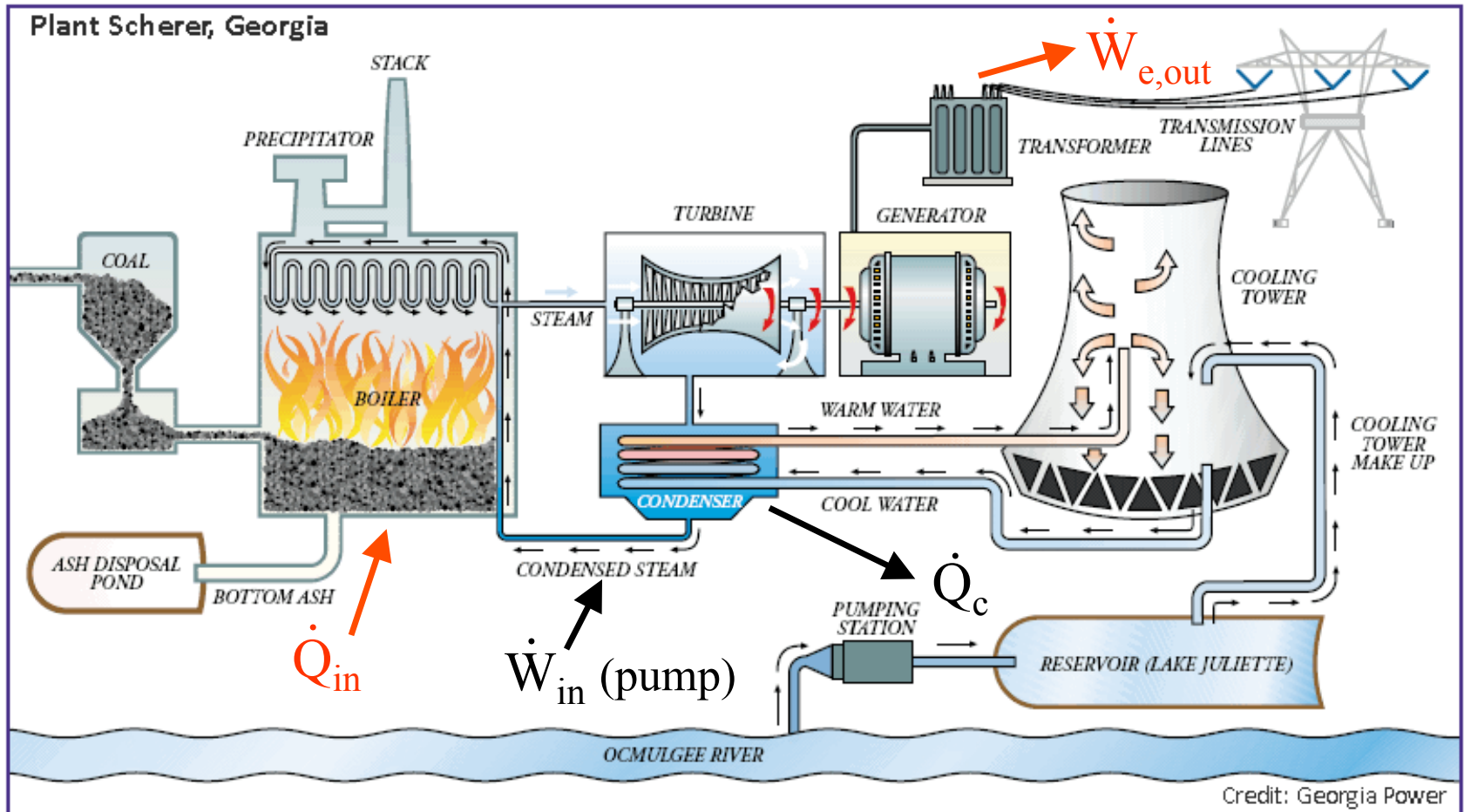


Delaware Generating Station, Philadelphia

[www.exeloncorp.com](http://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

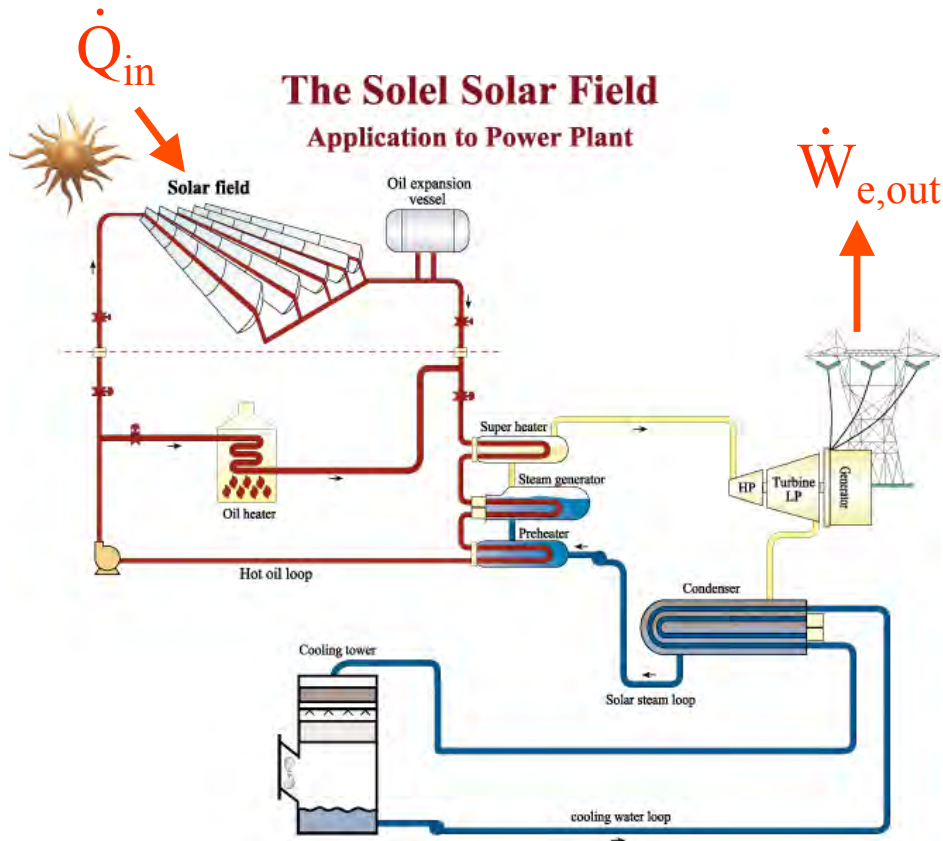
# Coal-Fired Steam Power Plant



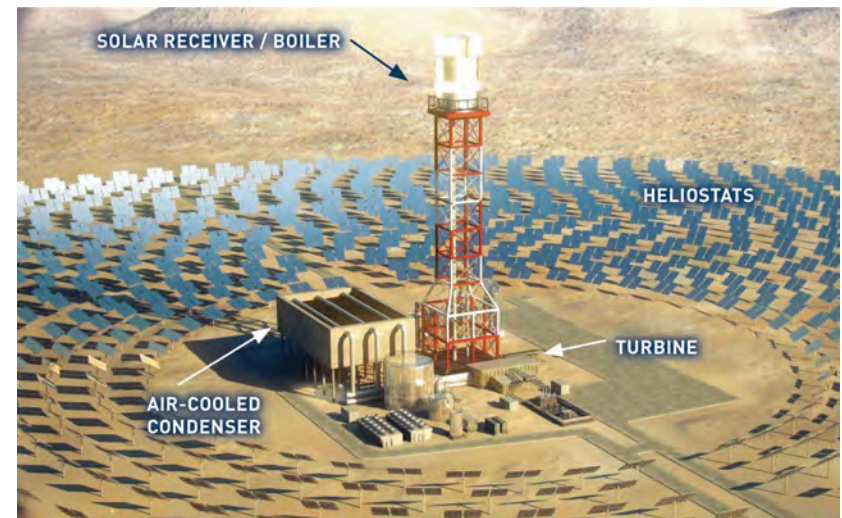
Put heat in, get electrical power out



# Solar Steam Power Plant



parabolic trough collector



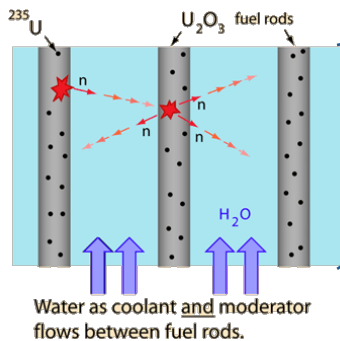
concentrating solar “power tower”  
*solar-trap.com*

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

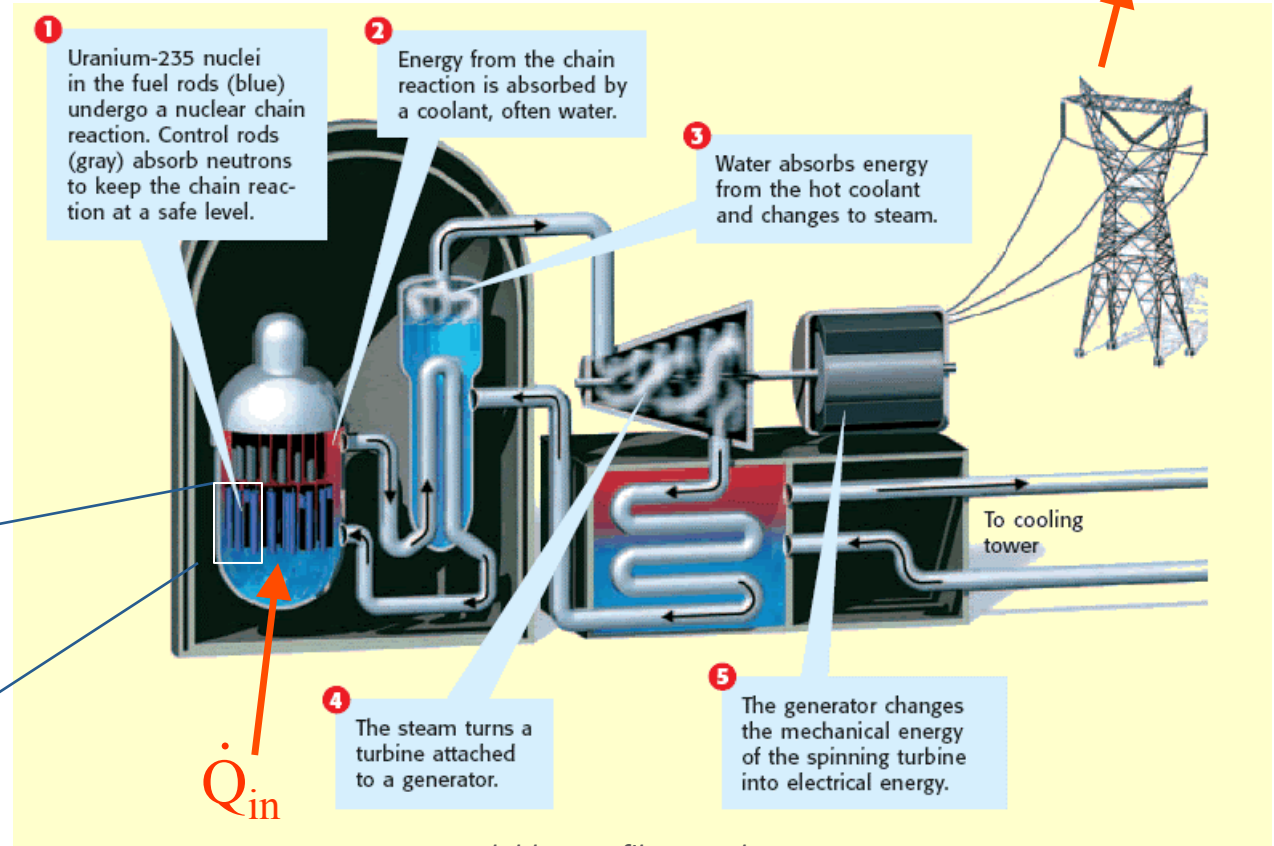
# Nuclear Power Plant



Three Mile Island



[hyperphysics.phy-astr.gsu.edu](http://hyperphysics.phy-astr.gsu.edu)



[edublognss.files.wordpress.com](http://edublognss.files.wordpress.com)

Main difference: heat comes from nuclear fissions

# Industrial Waste Heat Recovery

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Practical heat recovery systems for **oil refineries, cement and paper plants, power stations, steel & glass plants, incinerators** and any other industrial waste heat source.

## 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.

J. R. Lukes

## Reach Us

### PHOENIX THERMAL ENERGY CONVERSION

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

organic Rankine cycle

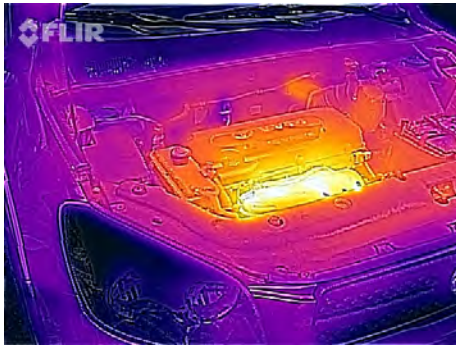


# Direct Energy Conversion

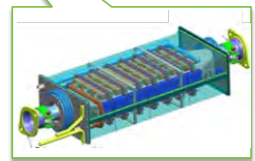
Heat → Electrical

# Automotive Energy Recovery

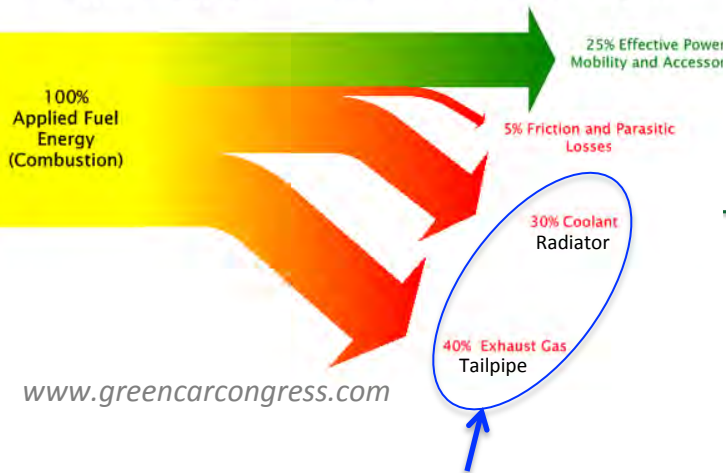
Vehicle Integration with Thermoelectrics: FORD, GM and BMW  
Prototype integration pursued under DOE/industry sponsorship



Chevy Suburban



Typical Energy Split in Gasoline Internal Combustion Engines



www.greencarcongress.com

70% of fuel energy is lost as heat

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

**Solid state thermoelectric energy conversion for improved fuel economy**

Fairbanks, 2013

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

# TEG Subsystems Modeling and Design

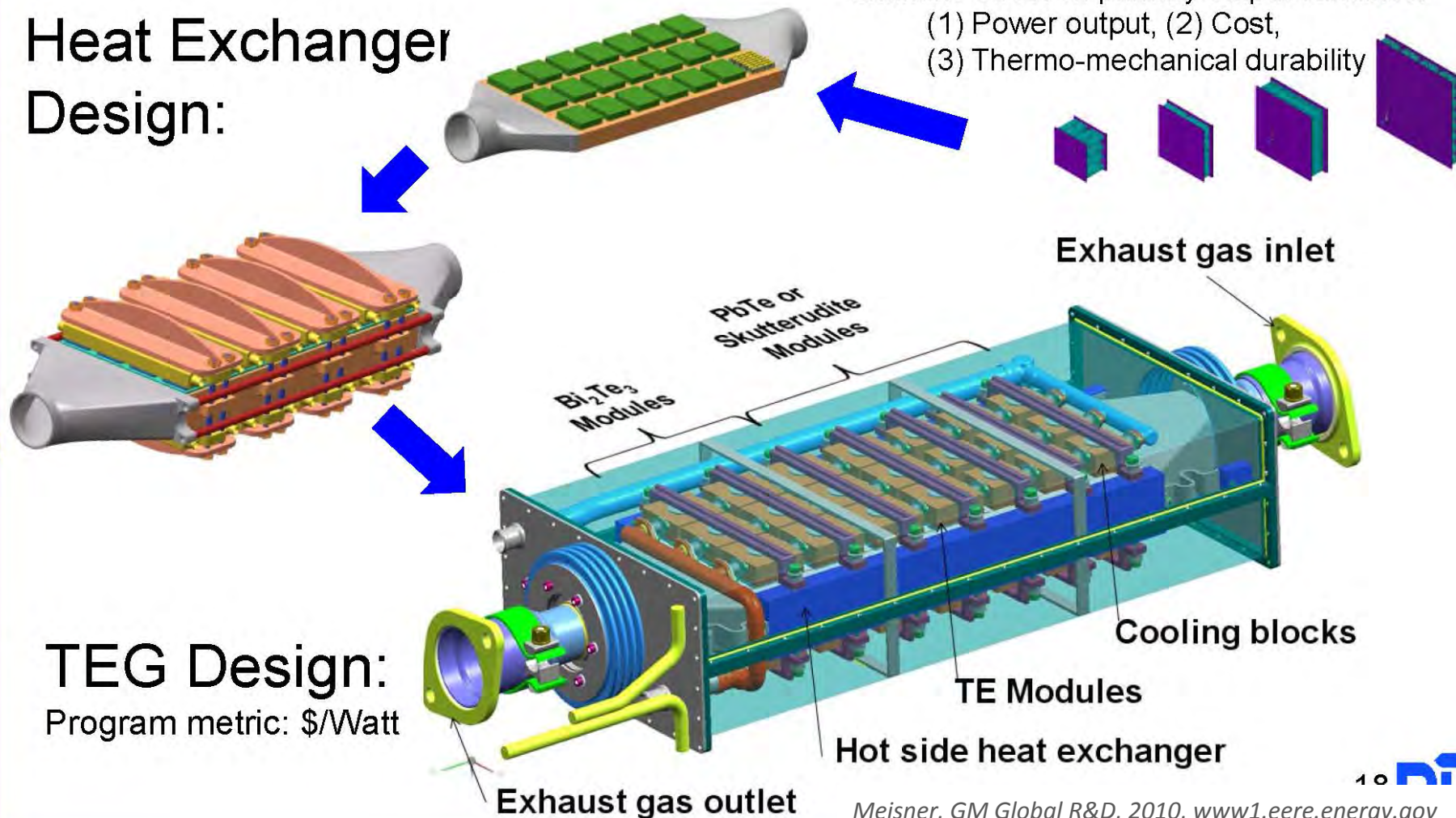
## TE Module Design:

Identify primary module design variables

Examine effect on primary output variables:

- (1) Power output, (2) Cost,
- (3) Thermo-mechanical durability

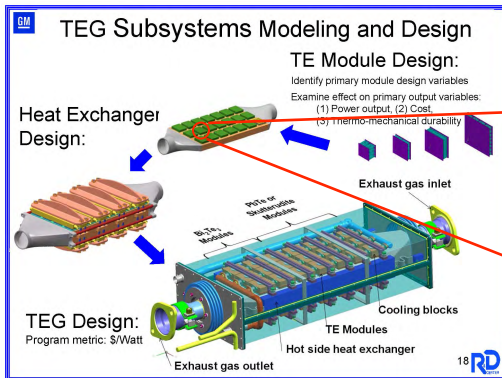
## Heat Exchanger Design:



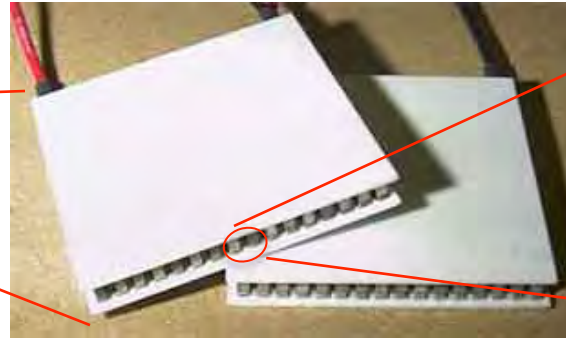
## TEG Design:

Program metric: \$/Watt

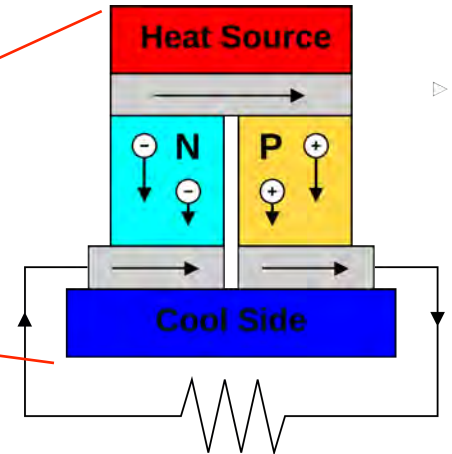
# Thermoelectric Module



Meisner, GM Global R&D,  
2010, [www1.eere.energy.gov](http://www1.eere.energy.gov)



[electronickits.com](http://electronickits.com)



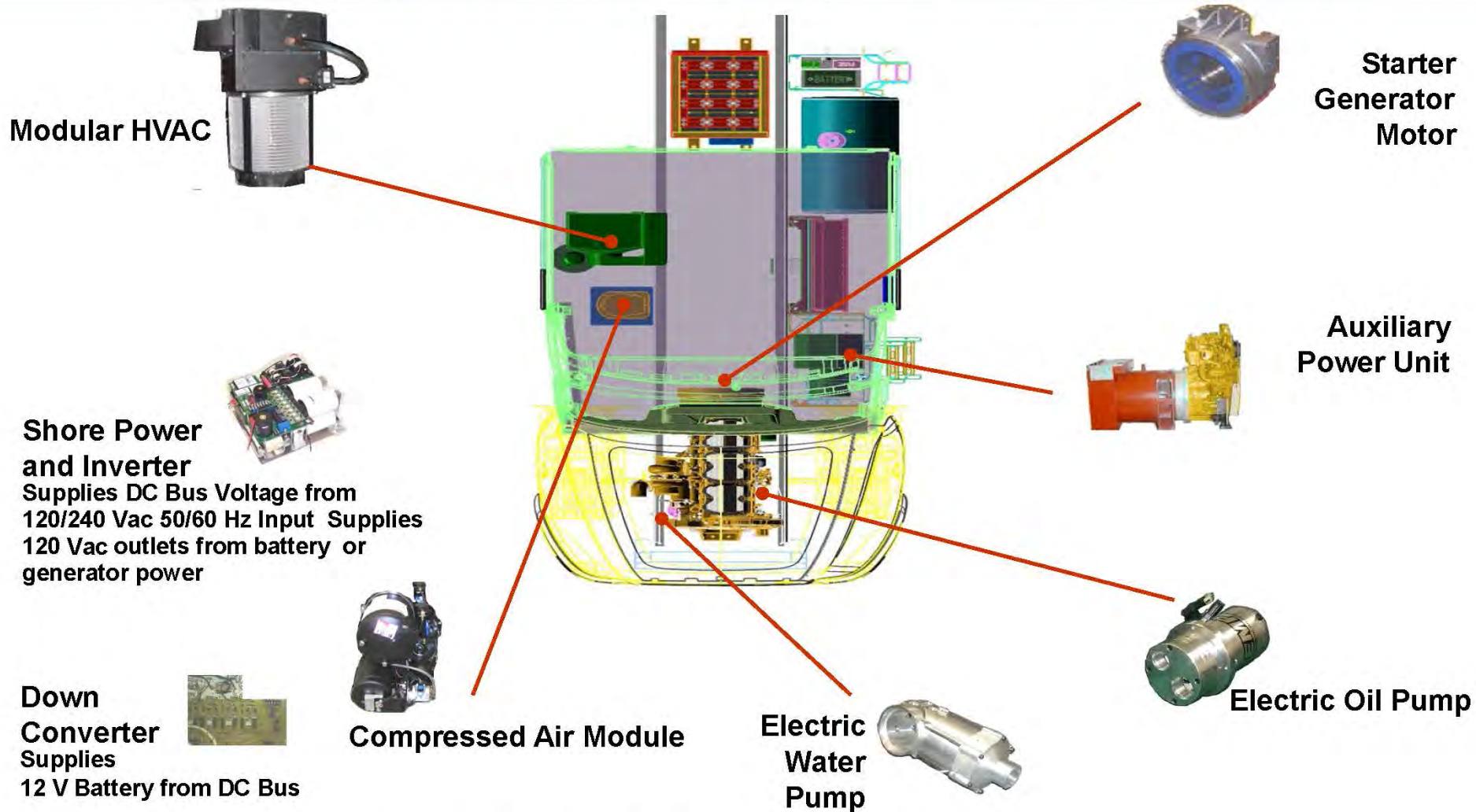
Brazier, Wikimedia Commons

## 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

# Climate

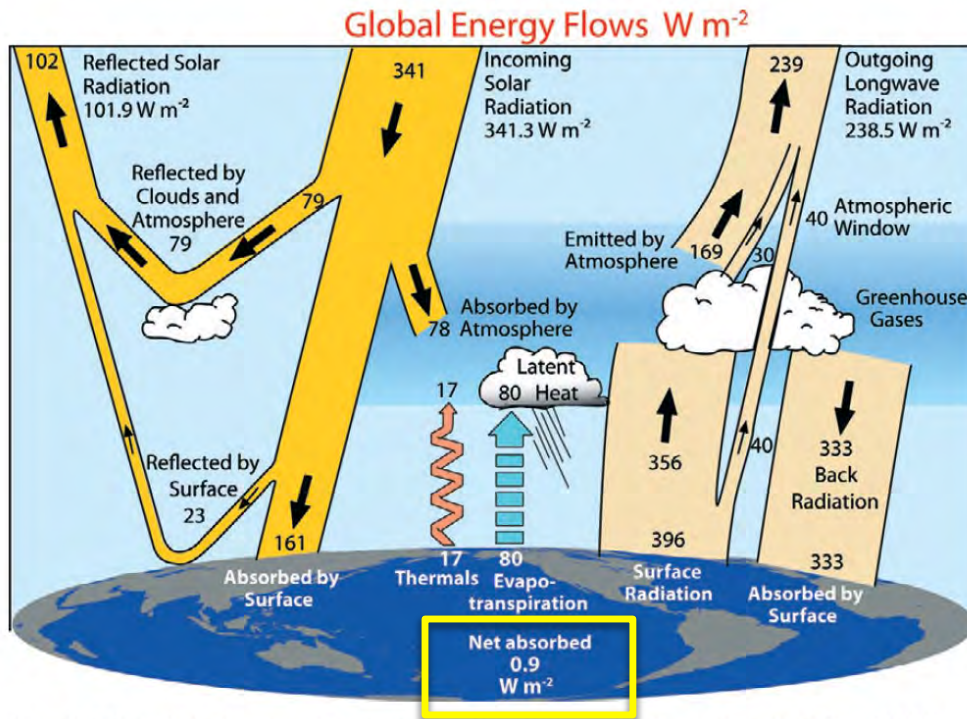
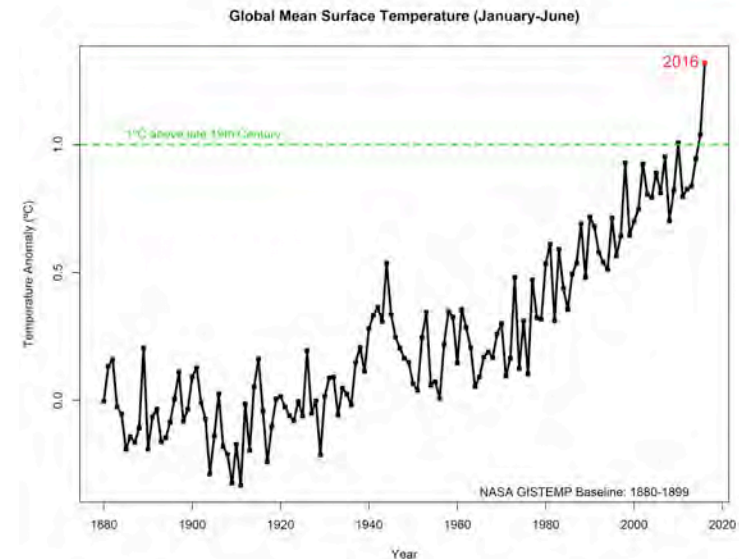
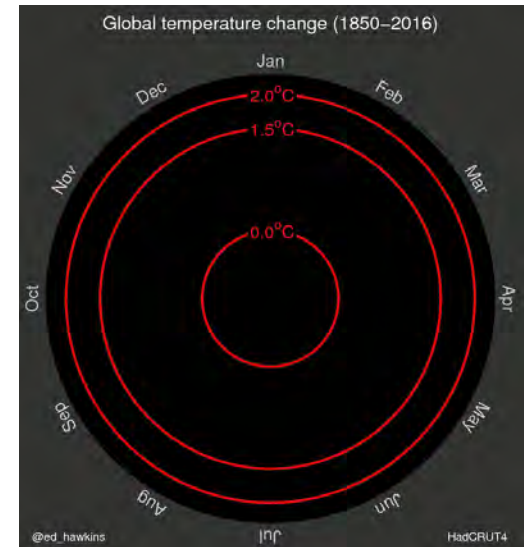


FIG. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period ( $\text{W m}^{-2}$ ). The broad arrows indicate the schematic flow of energy in proportion to their importance.

*Trenberth et. al, BAMS, 2009*

## Earth's thermal energy balance





# Health

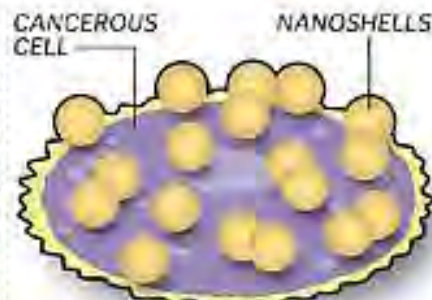
## FIGHTING TUMORS WITH NANOSHELLS

Scientists create tiny particles, each about 120 nanometers in width, with a core of glass covered by a thin gold shell. By varying the width of the glass core and gold shell, scientists can "tune" the shells to absorb light and heat up at various wavelengths.

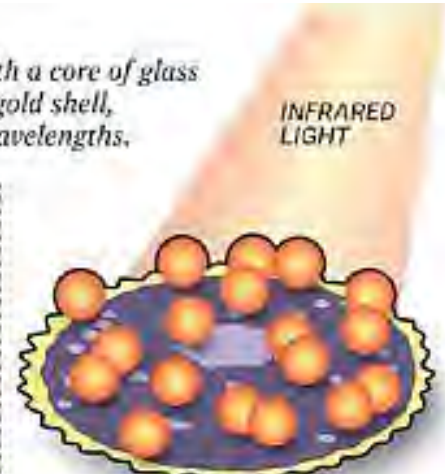


One of the most promising varieties of nanoshells strongly absorbs light at the near-infrared wavelength, which harmlessly passes through human skin.

Source: Nanospectra Biosciences



For treatment, a cancer patient receives a dose of nanoshells intravenously, and over the course of a day about 1 percent accumulate in a tumor. Most of the rest wash out.



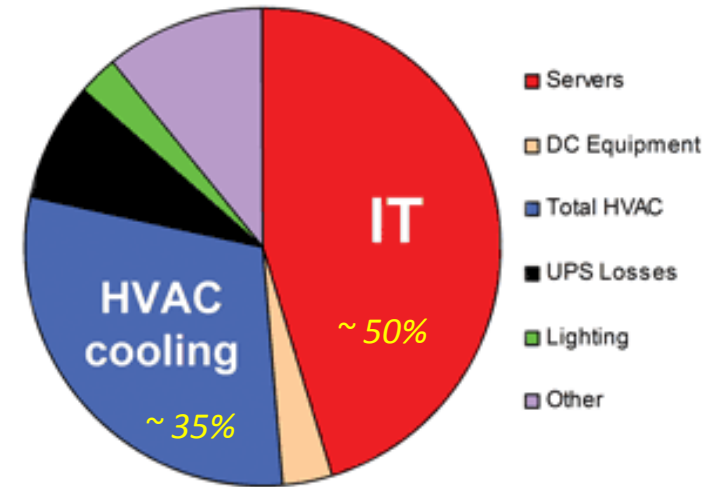
A physician then shines an infrared light over the tumor. The nanoshells heat up, burning away the tumor, while healthy cells nearby are unharmed.

ROBERT DIBRELL, ERIC BERGER : CHRONICLE

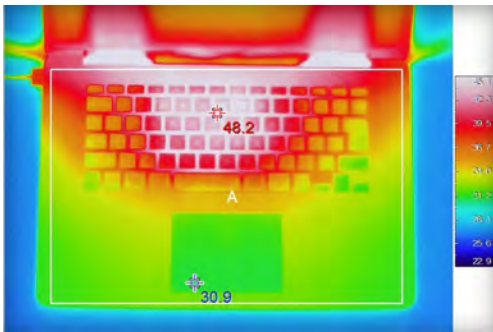
Hyperthermia to treat cancer



# Information Technology



Iyengar and Schmidt, 2010, electronics-cooling.com



www.sciencealert.com

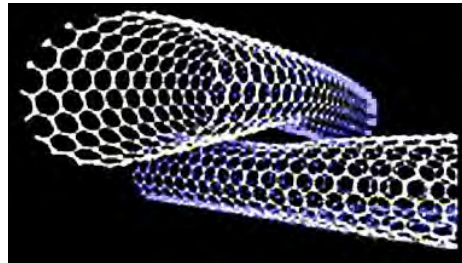
Cooling: a significant fraction of data center operating costs

# Lukes Group Research

# Overall Goal 1

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

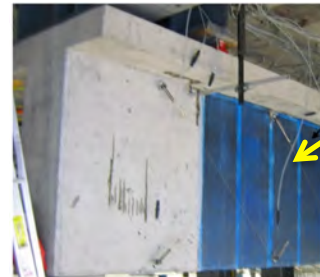
# Carbon Nanotube-Based Materials



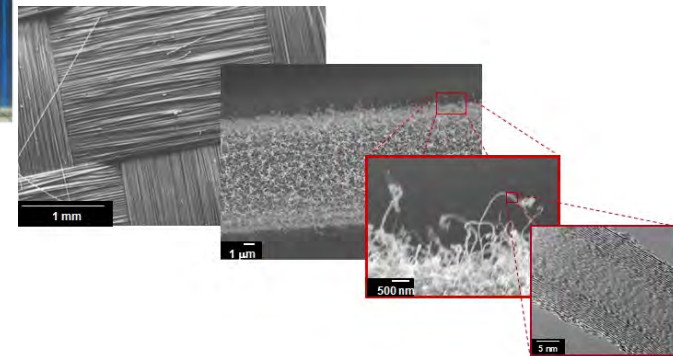
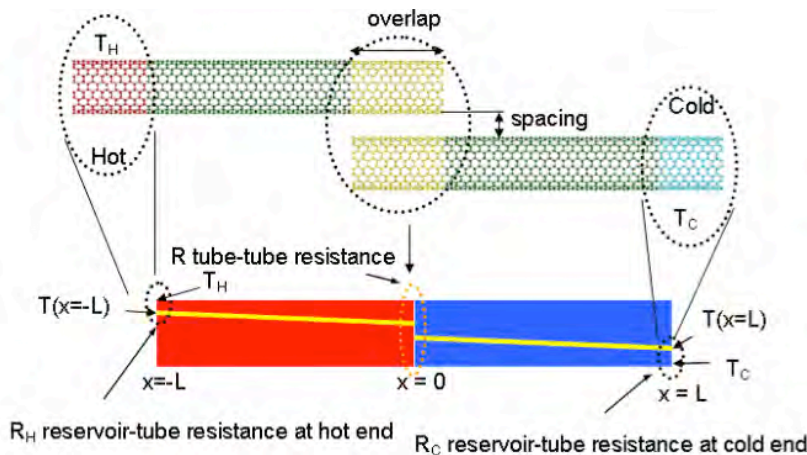
Nanotube-nanotube interface  
[www.staff.uni-mainz.de/banhart](http://www.staff.uni-mainz.de/banhart)

Electrically conductive nanotube-polymer networks for structural health monitoring

[sites.udel.edu/nsf-cmmi-cnt-shm](http://sites.udel.edu/nsf-cmmi-cnt-shm)



Nanotube-polymer sensors on section of bridge

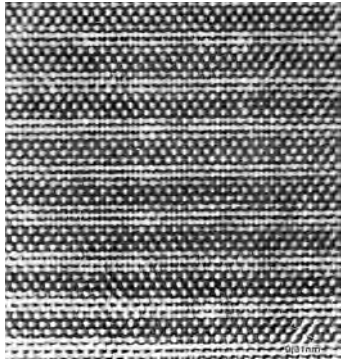


Hierarchical view of sensor structure

Thermal transport across nanotube-nanotube interface

*Zhong and Lukes, PRB, 2006*

# Superlattice-Based Materials



Superlattice atomic structure

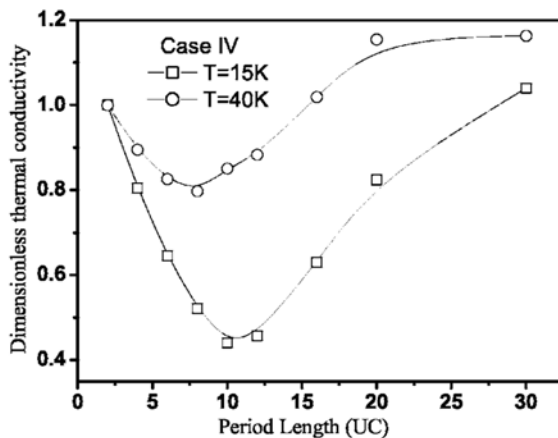
[www.tf.uni-kiel.de/matwis/ama](http://www.tf.uni-kiel.de/matwis/ama)

Enhanced ultraviolet light detectors  
for space applications



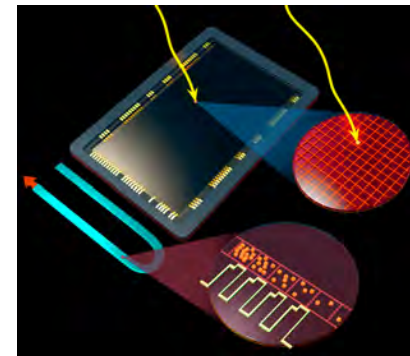
Hubble Space Telescope floating over Earth

NASA, 2009



Minimum superlattice thermal conductivity

Chen et al., PRB, 2005



Electron multiplying charge coupled device

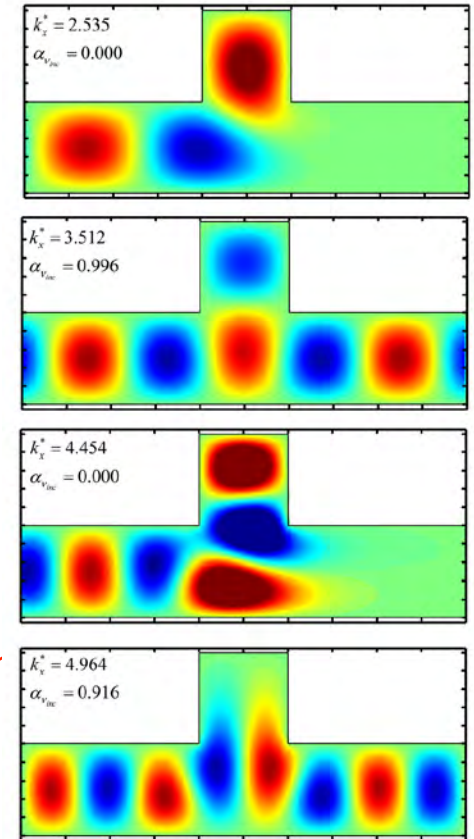
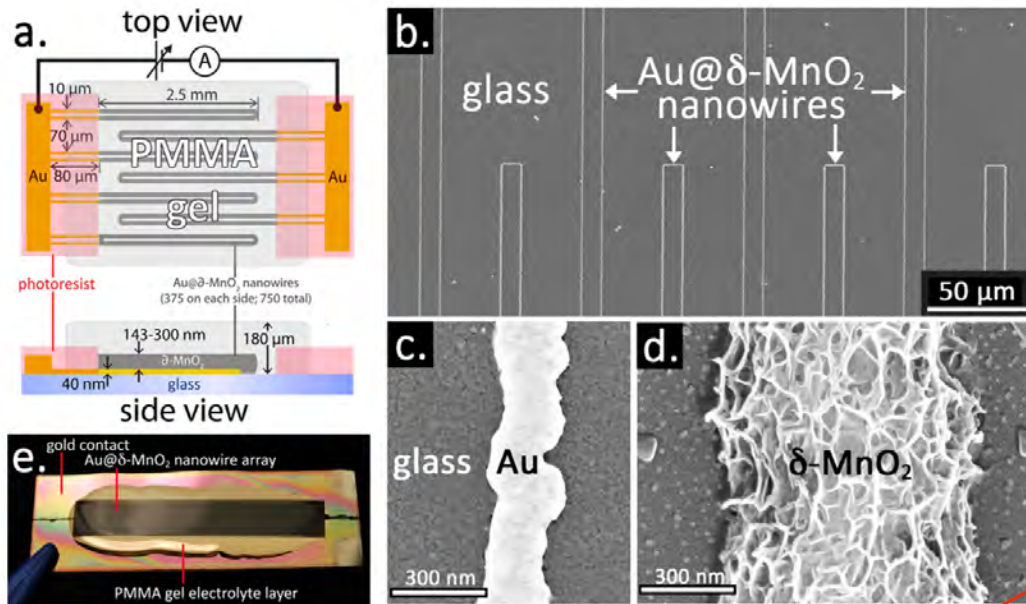
NASA, 2009



# Nanowire Arrays

## Flexible, stable nanowire batteries

Thai et al., ACS Energy Letters, 2016

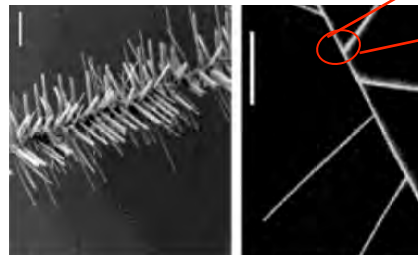


Controlling transport of phonons  
by tuning nanostructure

Cheney and Lukes, JHT, 2013

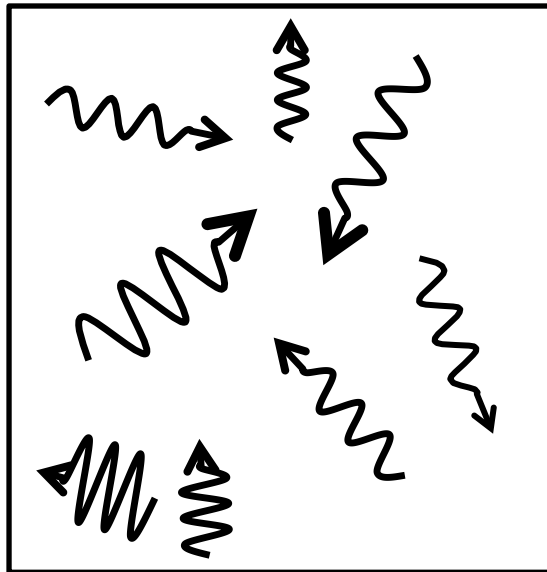
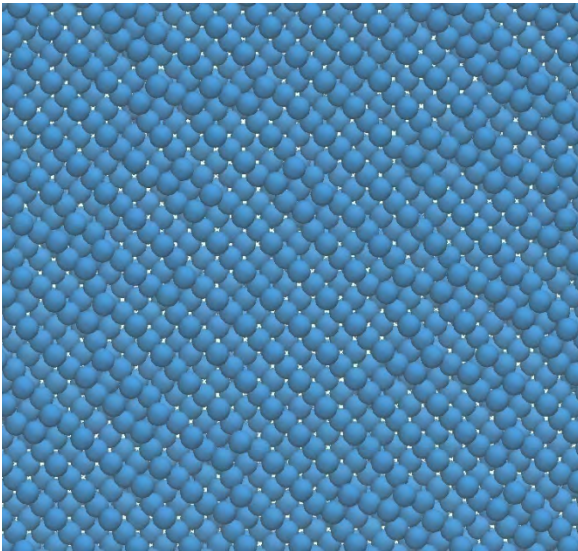
## Branched nanowires

Wang et al., Nano Lett., 2004



# What is a Phonon?

## Thermal vibration of atoms in a material



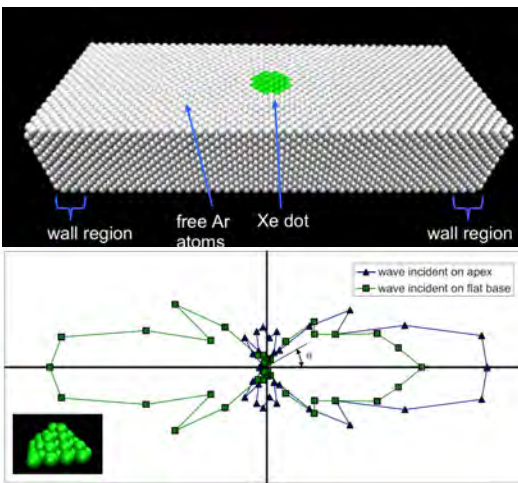
- Many different vibrational modes
- Travel in all directions
- Scatter off of each other, boundaries and material impurities

# 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*

Reducing thermal conductivity  
using nanostructures

Thermoelectric  
module

*electronickits.com*

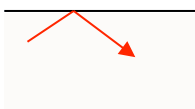


**NO BACKSCATTERING**  
Higher conductivity

*no nanoparticles*

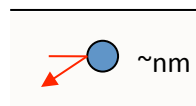


*smooth interface*

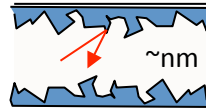


**BACKSCATTERING**  
Lower conductivity

*nanoparticles*

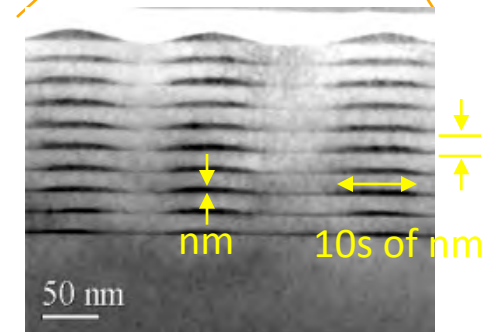


*nano-rough interface*

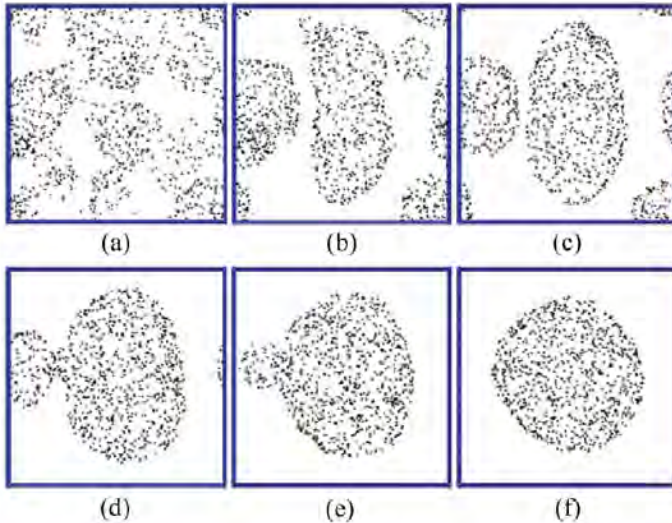


Silicon/germanium  
quantum dot  
superlattice

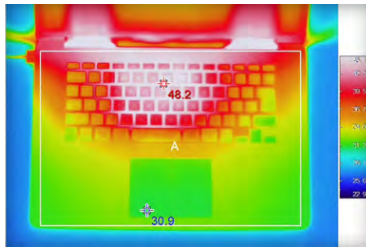
*web.chemistrymag.org*



# How do Bubbles Form at Nanotextured Interfaces?



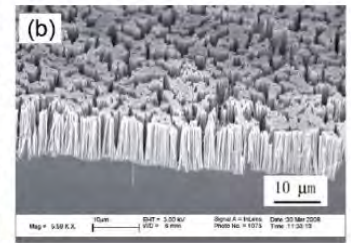
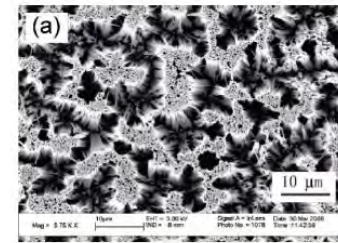
Nucleation and coalescence of vapor bubbles  
*Cosden and Lukes, JHT 2011*



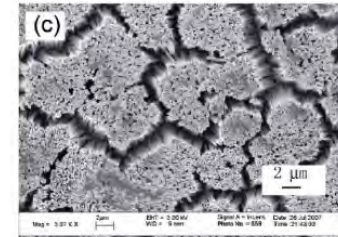
[www.sciencealert.com](http://www.sciencealert.com)

100% enhancement in cooling performance with nanowire coated surfaces

Si NWs  
→



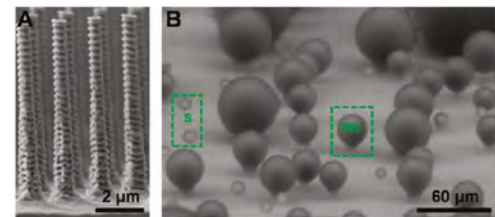
Cu NWs  
→



Nanowire coated surfaces  
*Chen et al. Nano Lett., 2009*

# How do Droplets Form at Nanotextured Interfaces?

Enhanced ability to condense steam and collect clean water

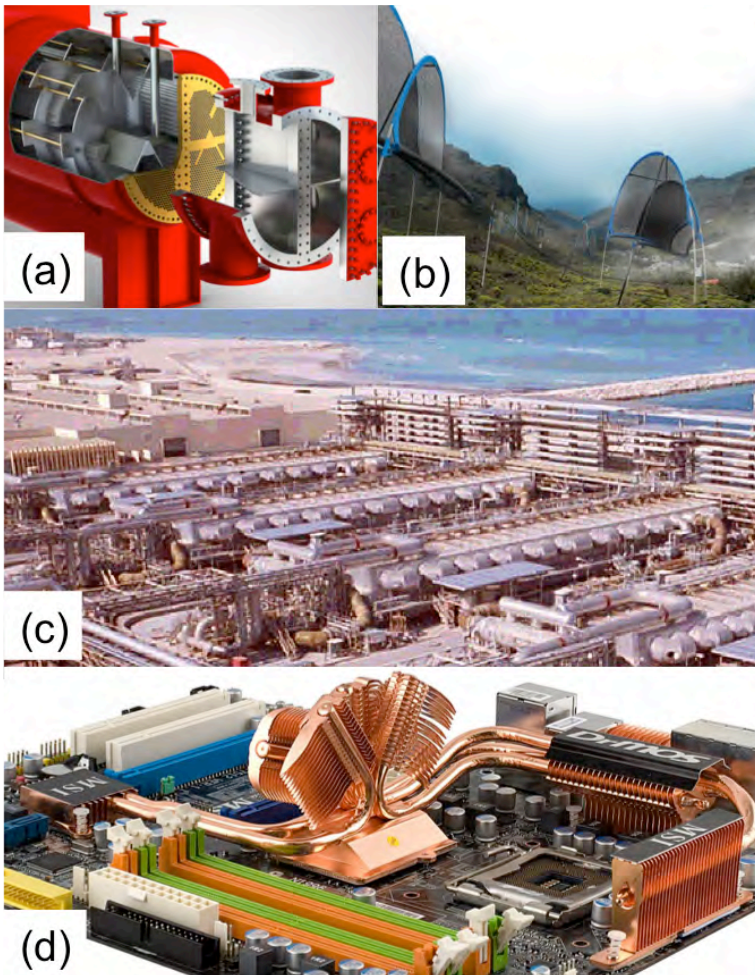
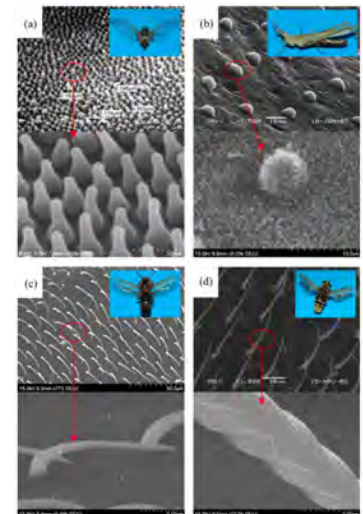


Droplet condensation on silicon nanopillars

*Miljkovic et al., ACS Nano, 2012*

Hierarchical micro/nano structures on insect wings

*Byun et al., JBE, 2009*



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

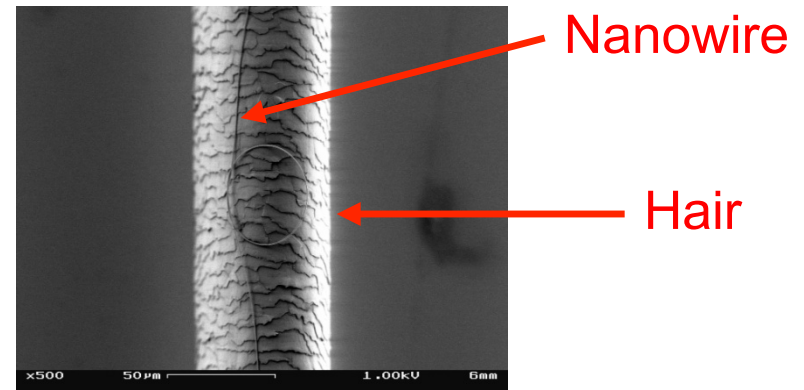
# Research Methodology

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

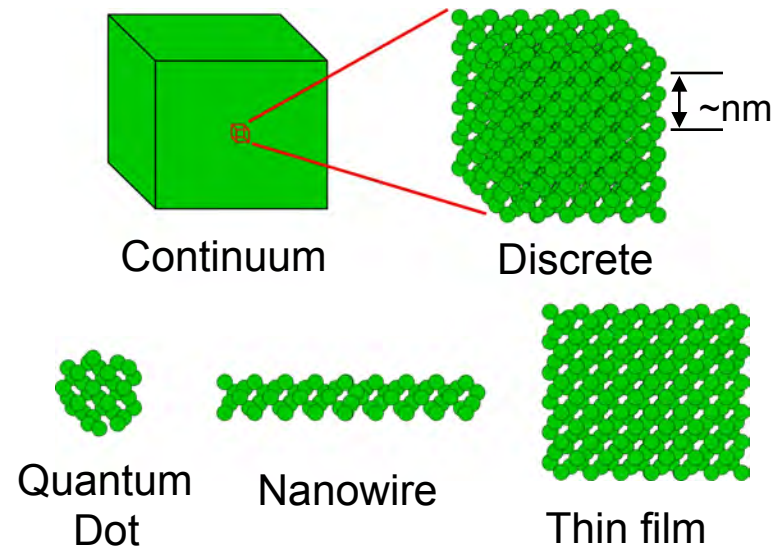


# What is Different about “Nano” ?

- 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**

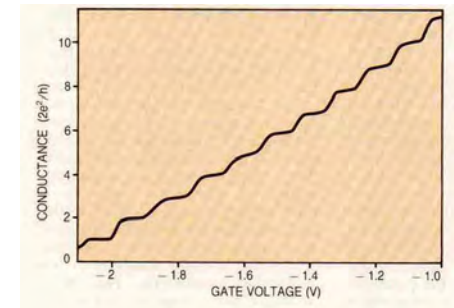
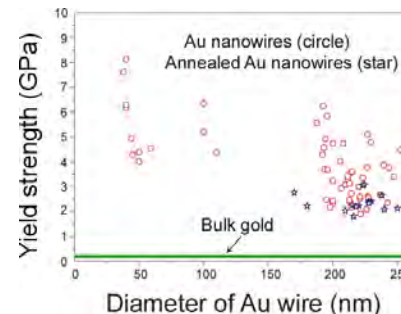
- Size selectivity of emitted light color



*Increasing quantum dot size →*

- **Mechanical**

- Diameter-dependent yield strength of Au nanowires<sup>1</sup>



- **Electronic**

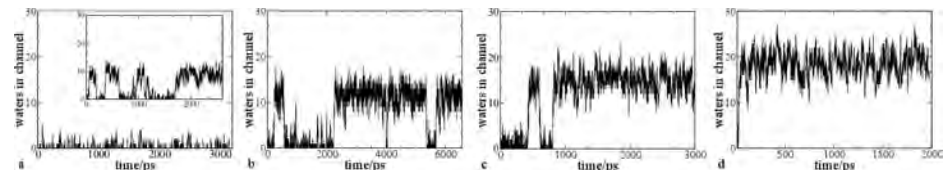
- Quantized conductance in channels<sup>2</sup>

- **Thermal**

- Low nanowire and high nanotube conductivity

- **Fluidic**

- Increased viscosity
- Intermittent nanopore permeation by water<sup>3</sup>



*Increasing pore size →*

<sup>1</sup>Wu, Heidelberg, Boland, *Nature Materials* **4**, 525, 2005

<sup>3</sup>Allen, Melchionna, Hansen, *PRL* **89**, 175502, 2002

<sup>2</sup>Khurana, *Physics Today*, **21**, Nov. 1988

J. R. Lukes

# 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](http://www.theaustralian.com.au)

## Control direction of heat flow

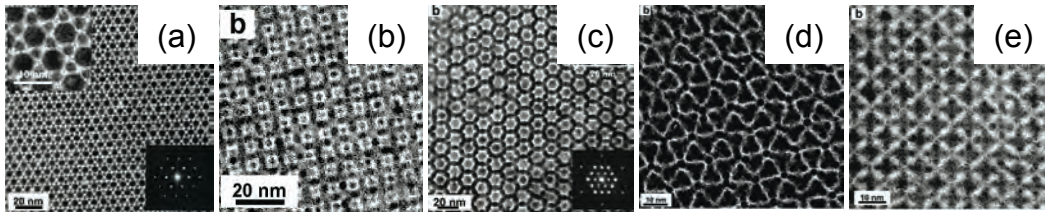
*better thermal management*

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

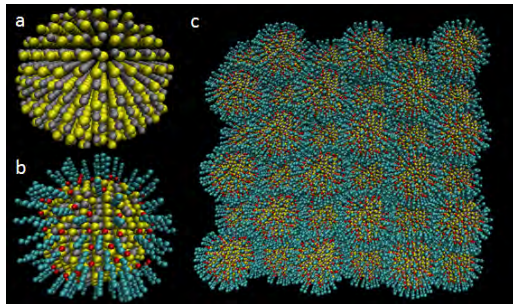
# Nanocrystal Superlattice Thermal Conductivity



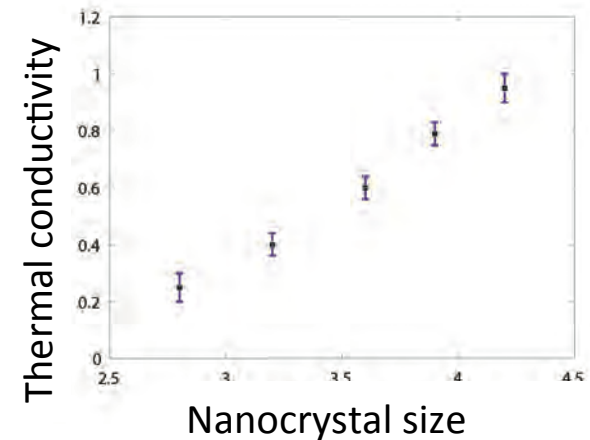
Dr. Mehdi Zanjani



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



Computer model of CdSe NSL



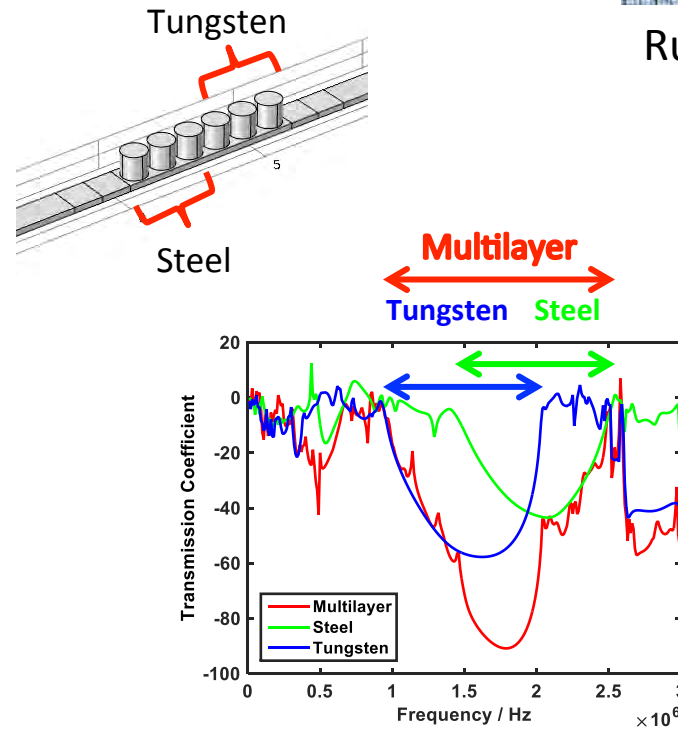
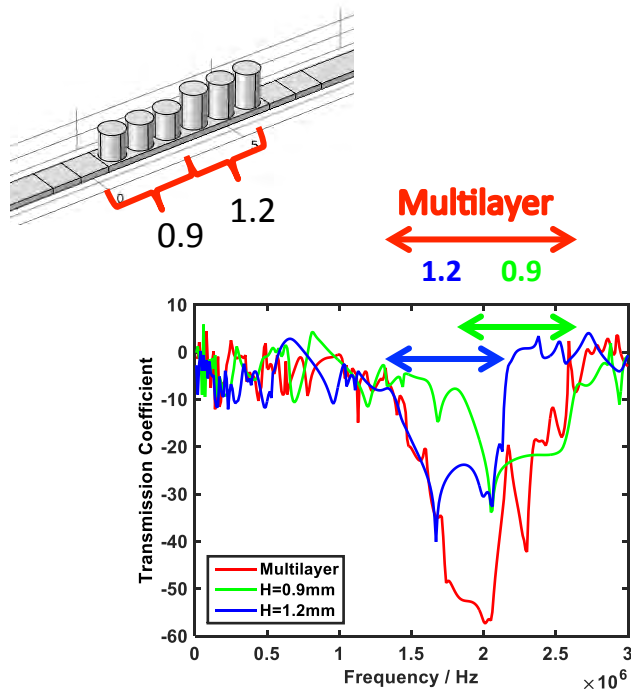
- Vast range of NSL structures
- Thermal conductivity of NCSL increases with size of nanocrystal core
- Tunable structures → “materials by design” for thermal applications
- Atomistic modeling needed to properly capture correct material properties



# Multilayer Phononic Crystals to Reduce Heat Transmission



Ruiyuan Ma

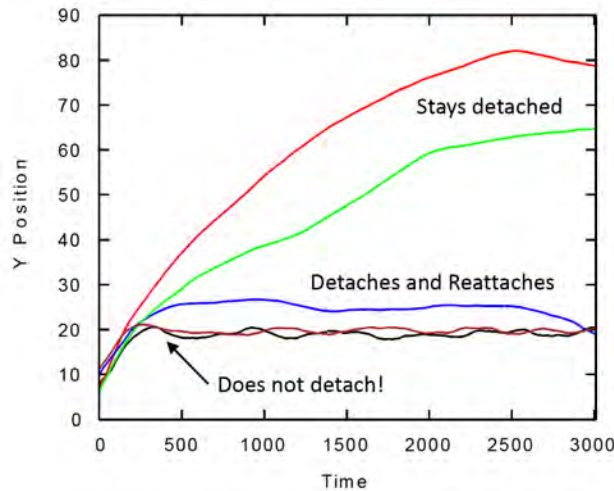


- Band gaps in multilayer structures are larger than those of uniform materials
- Wider band gaps  $\rightarrow$  reduced heat transmission
- Shape, size, spacing, and composition can be used to tune the band gap

# Droplet Jumping from Nanostructured Surfaces



Paul Barclay



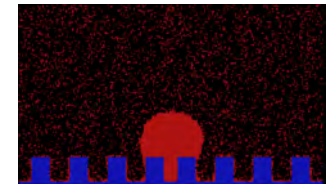
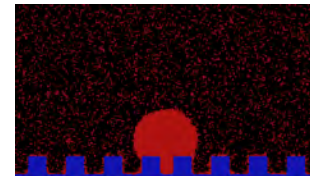
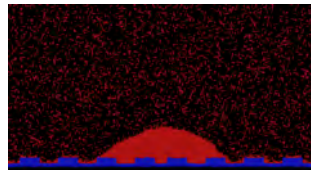
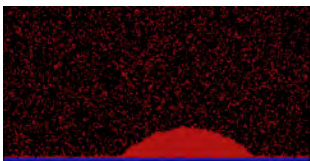
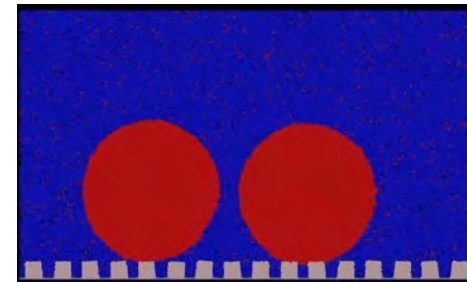
Smooth Black

$$p_H \approx 4.27$$

$$p_H \approx 8.55$$

$$p_H \approx 12.82$$

$$p_H \approx 17.10$$

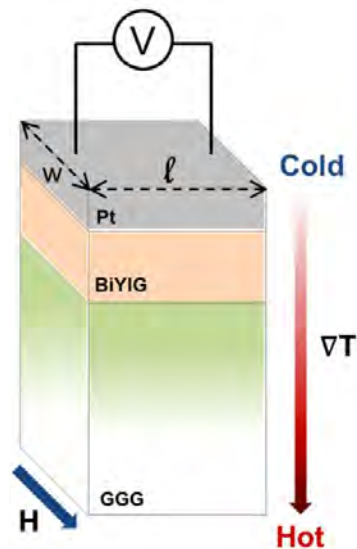


- Geometry of surface determines whether and how high droplets jump
- Jumping → better heat removal from condenser surface
- Higher pillars are not always better

# Thermal to Electric Energy Conversion in Magnetic Insulators

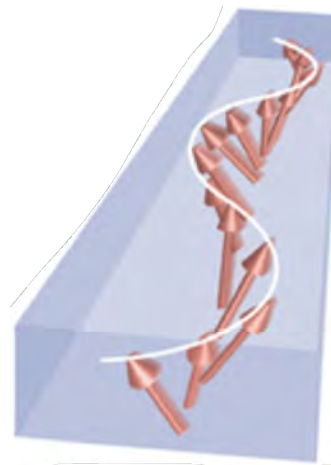


Joe Cooke



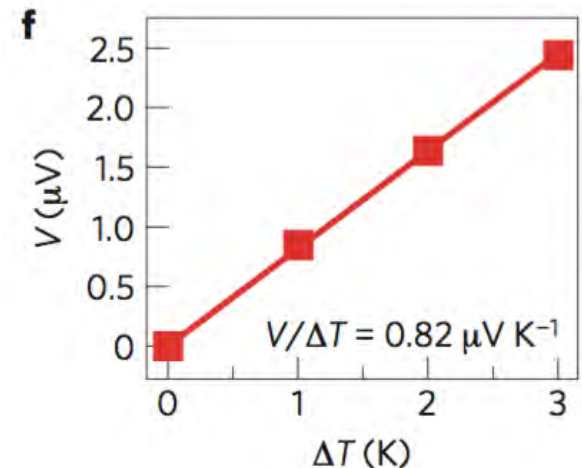
Longitudinal Spin Seebeck Effect

Siegel et al., Sci. Rep. 2014



Spin Wave

Kajiwara et. al, Nature, 2010



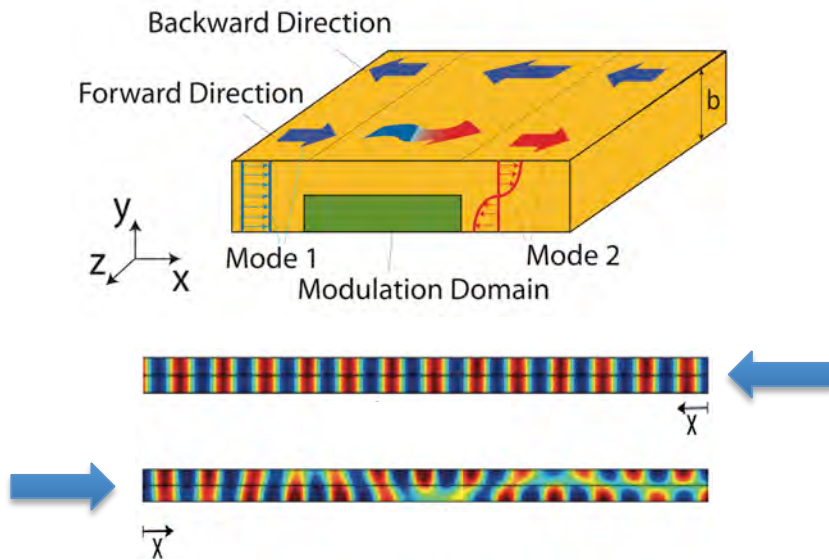
LSSE Voltage

Kirihara et al., Sci. Rep. 2012

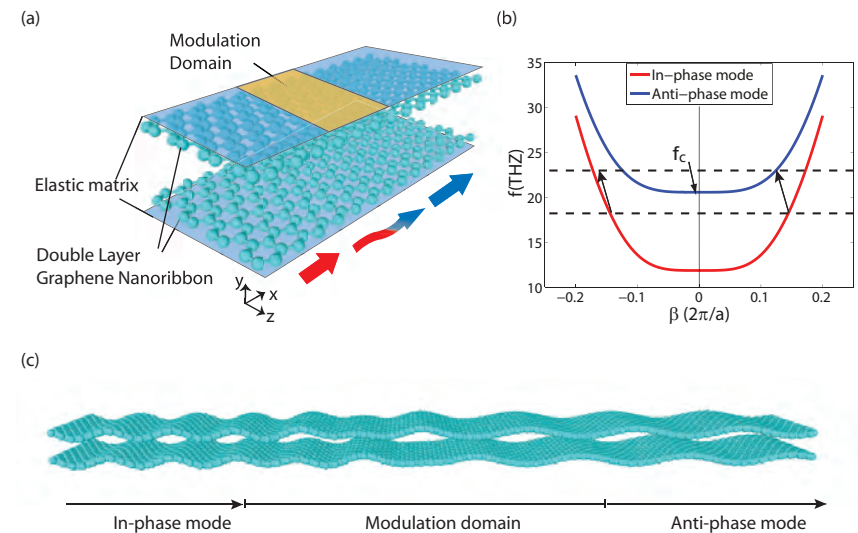
- Temperature gradient across magnetic layer drives a spin current
- Spin current creates voltage in the metallic layer ( $V$  proportional to  $\Delta T$ )
- Currently developing models to capture thermal-magnetic coupling

# 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

