Using Nanotechnology for Novel Energy Applications

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What is Nanotechnology?

Nanotechnology: Technology at the **nanometer** length scale

Nanometer: 10^{-9} or 0.000000001 meter

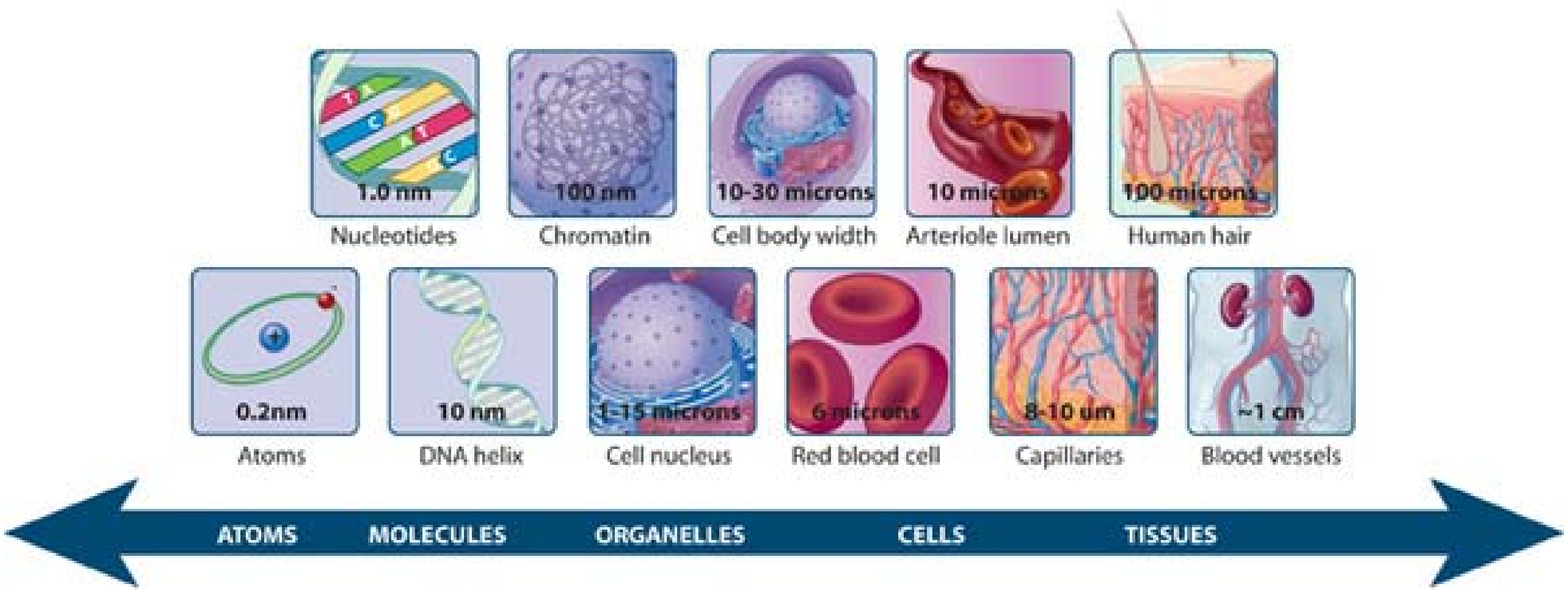
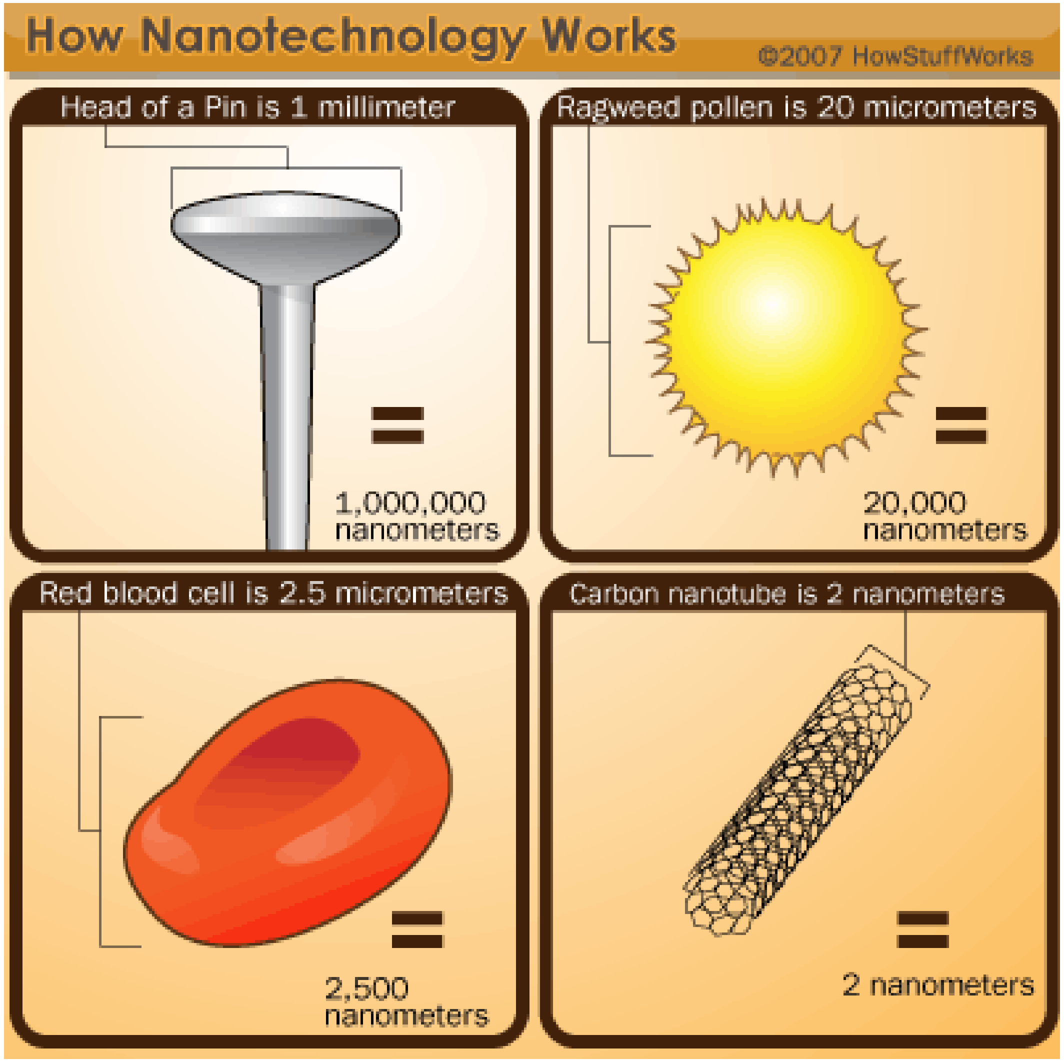


Image: “Scitable” by Nature Education

http://www.howstuffworks.com/nanotechnology.htm



…Unprecedented multidisciplinary convergence of scientists dedicated to the study of a world so small, we can't see it. …

Nanotechnology is so new, no one is really sure what will come of it…

The Beginning

- The idea of nanotechnology began with famous physicist **Richard Feynman**

  "I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle…

  What I want to talk about is the problem of manipulating and controlling things on a small scale "

The Beginning

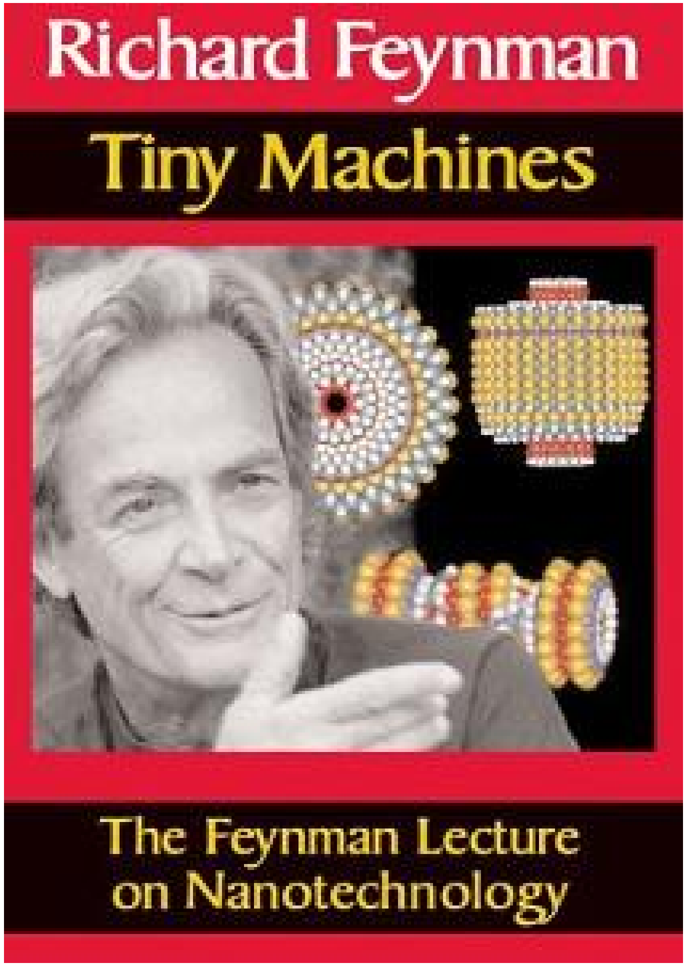
•1959, APS meeting, Caltech

"There's Plenty of Room at the Bottom"

"The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom."

Feynman proposed using a series of robot arms construct ever-smaller robot arms, until the arms get so small that they are able to manipulate individual atoms.

The Beginning



…''Amusing,
entertaining,
informative
and a classic
in the history of
nanotechnology.''

http://photosynthesis.com/Nanotechnology.html

What is so Special about Nanotechnology?

Nanotechnology can:

- **Make things smaller** – allowing us to make extremely small devices (such as implantable devices). Also allows to fit more technologies onto a chip

- **Enable Revolutionary Technologies** that have no macro-scale equivalents. Physics behaves very differently at the nano-scale, and we can utilize these new physical properties to develop technologies and products that would be impossible without nanotechnology.

How can you study Nanotechnology?

- These devices are much smaller than we can see with our eyes, or even under a regular microscope.
- We need special tools to create or even “see” nano structures
- These tools must be kept in special labs that isolate the devices from:
  - **Vibrations** – even small movements can make it impossible to see or create the structures
  - **Dirt and dust** – just one piece of hair is about 10,000 times larger than the nanostructures, and can completely destroy the device’s operability
  - **Humidity, and temperature changes** also have a large impact on the nanostructures’ physical properties and affects the materials’ performance

This is why we built the building you are in right now!

Birck Nanotechnology Center

- Built in 2005 for $58 Million (excluding equipment)
- Specially designed to reduce and eliminate **vibrations, dirt and dust, humidity and temperature changes**
- **Largest and cleanest** university cleanroom in the United States
- Entire building: 187,000 sq. ft., Cleanroom: 25,000 sq. ft., and Additional Lab Space: 22,000 sq. ft.
- 180 graduate students, 45 faculty, 21 clerical and technical staff

Research at the BNC

Nanophotonics to control and manipulate light on the nanometer length scale

Nanoelectronics to develop smaller and faster electronic devices

Nanobiotechnology to study biological systems at the nanometer scale

Nanomaterials to create and study new materials at the nanometer length scale

Nanoelectromechanical systems to create and study moving systems at the nanometer length scale

Who does research at the BNC?

The Students and Professors you will meet today!

Using Nanotechnology for Novel Energy Applications

Nanophotonics, **Nanoelectronics**, **Nanobiotechnology**, **Nanomaterials, Nanoelectromechanical systems**

Each of these topics are showing great promise for the future of energy collection, generation, storage, and efficiency

Today, we will discuss:

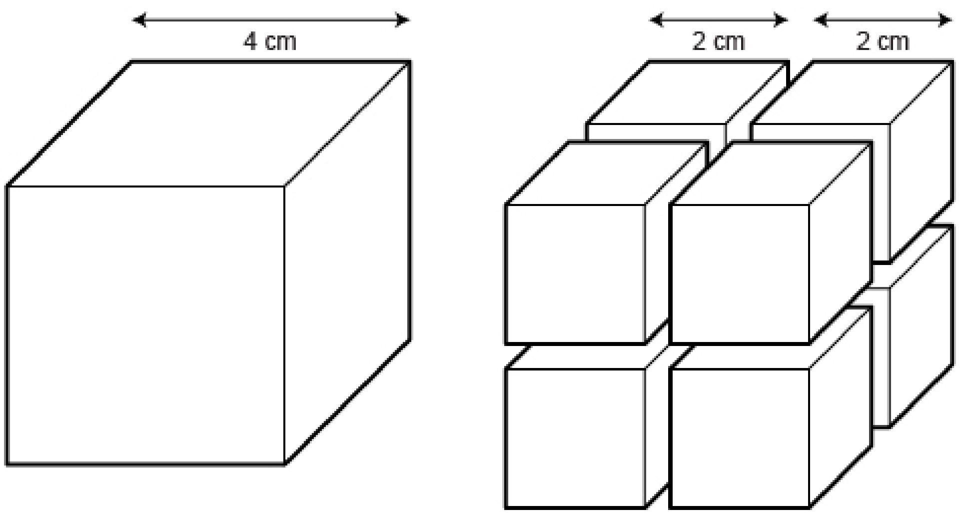
1. **Thermoelectrics:** Scott Finefrock & Sumeet Kumar
2. **Photovoltaics:** Caleb Miskin
3. **Nanophotonics:** Paul R. West

Tour of our building

Fundamental Concepts

Scaling down the size of materials to the nanoscale provides new physical phenomena including:

- Electronic properties of solids (nanoelectronics)
  - Amount of surface area drastically affects a material's electronic properties

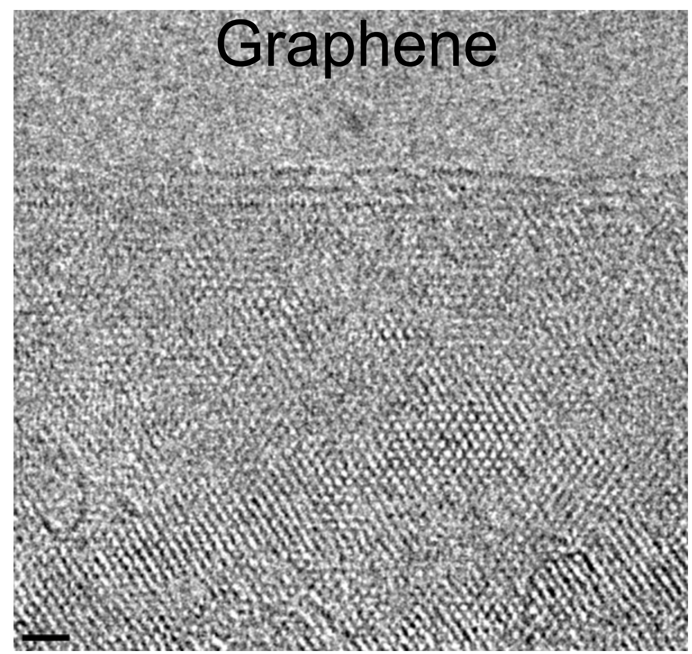


Surface area
= (4 cm x 4 cm x 6 faces) = 96 cm^2

Surface area of one cube
= (2 cm x 2 cm) x 6 faces = 24 cm^2

Total surface area
= 24 cm^2 x 8 cubes = 192 cm^2

Image courtesy of BBC News GCSE Bitesize

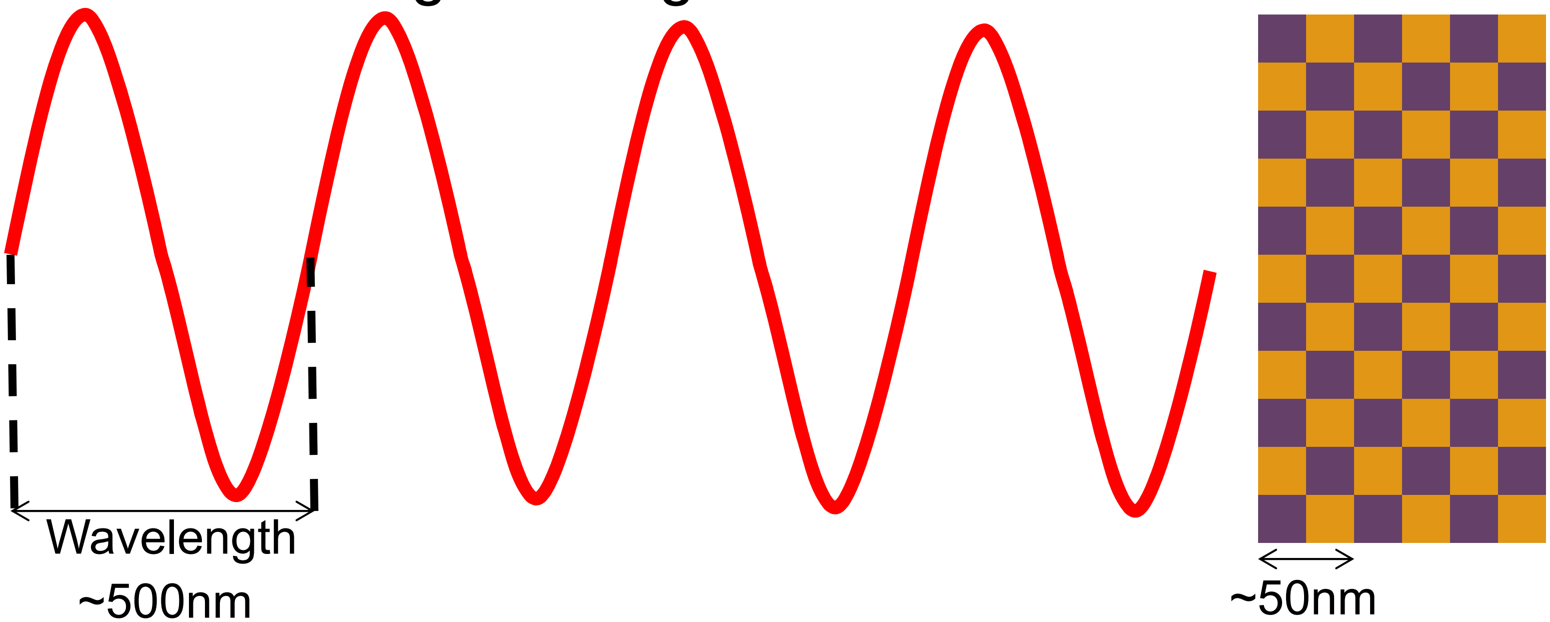


Jannik C. Meyer, et. al, Nature 446, 2007

Fundamental Concepts

Scaling down the size of materials to the nanoscale provides new physical phenomena including:

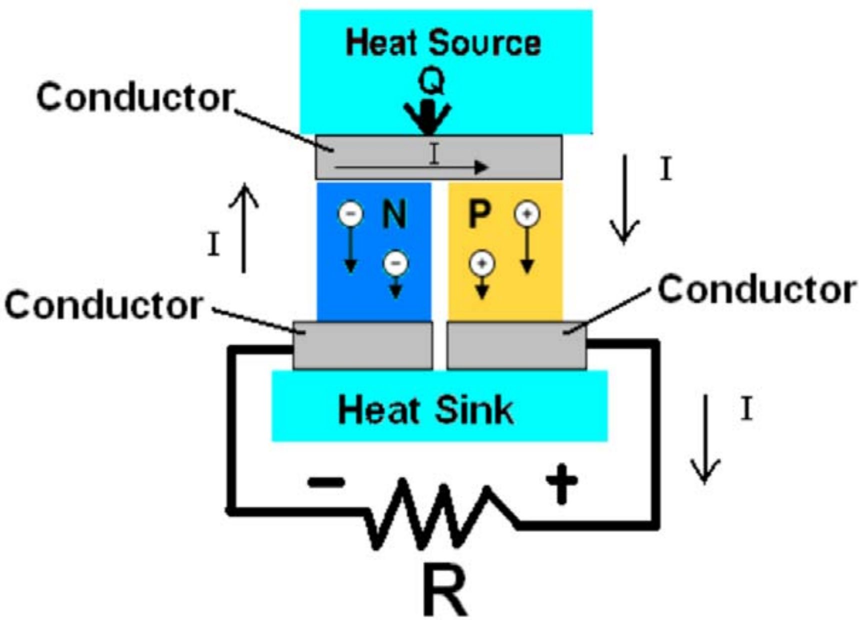
- Optical Properties (nanophotonics)
  - -Drastically new optical properties arise when a material is the same size or smaller than the wavelength of light



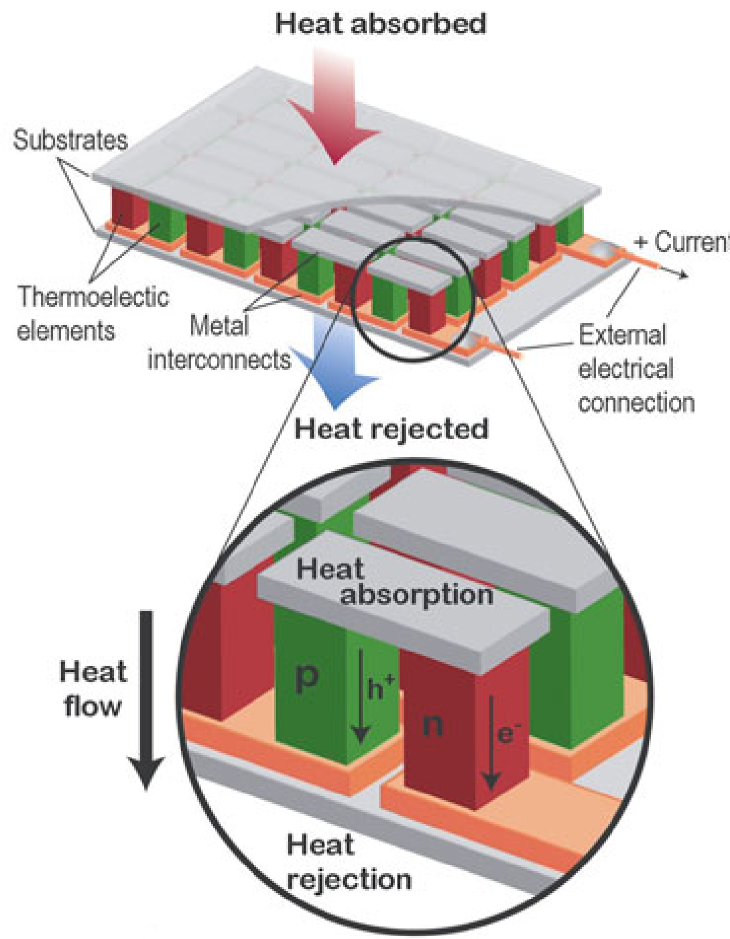
Thermoelectrics:
Power Generation, Cooling, and Nanomaterials

Sumeet Kumar – Purdue Mechanical Engineering
Scott Finefrock – Purdue Chemical Engineering
Professor Timothy Fisher – Purdue Mechanical Engineering

How does a thermoelectric generator work?



Top side is hot, bottom side is cold
Electrons carry heat so they move from hot to cold
Moving electrons create usable electric power!



Stratified Schematic of a thermoelectric module

Image taken from: Nemir D., Beck J., Rubio E. & Alvarado M, "Materials for Energy: Solid state Thermoelectric Generation", 2010

Image taken from: Snyder G.J.& Toberer E.S., "Nature Materials" **7**(2008) 105-114

Thermoelectric materials

Question: How do I measure how good a thermoelectric material is?

Answer: ZT

Higher ZT → Higher Efficiency

$$ZT = S^2\sigma T/k$$

<u>Seebeck coefficient (S)</u>

- How much energy do heat-carrying electrons have?

<u>Electrical conductivity (σ)</u>

- How easily do electrons move?

<u>Thermal conductivity (k)</u>

- How easily does heat move?

What materials have high ZT?

ZnO ? | Bi_2Te_3 ? | Cu ?

Material	Material type	|S|	σ	k	ZT (room temperature)
ZnO	Insulator	350	10^1	50	10^{-3}
Bi_2Te_3	semiconductor	200	10^4	1	1
Cu	Metal	7.6	10^7	400	10^{-3}

Ma, N., Li, J.-F., Zhang, B. P., Lin, Y. H., Ren, L. R., & Chen, G. F. (2010). *Journal of Physics and Chemistry of Solids*, *71*(9), 1344-1349.
Allison, S. C., Smith, R. L., Howard, D. W., González, C., & Collins, S. D. (2003). *Sensors and Actuators A: Physical*, *104*(1), 32-39.
Copper. (2012, June 04). Retrieved from http://en.wikipedia.org/wiki/Copper
Telluride Chemical. Triveni Interchem Private Limited. (2012, June 06). Retrieved from http://www.triveniinterchem.com/telluride.html
Zinc Oxide. (2012, June 06). Retrieved from http://en.wikipedia.org/wiki/Zinc_oxide
Yan, X., Poudel, B., Ma, Y., Liu, W. S., Joshi, G., Wang, H., Lan, Y., et al. (2010). *Nano letters*, *10*(9), 3373-8.

How can nanoscale materials have higher ZT?

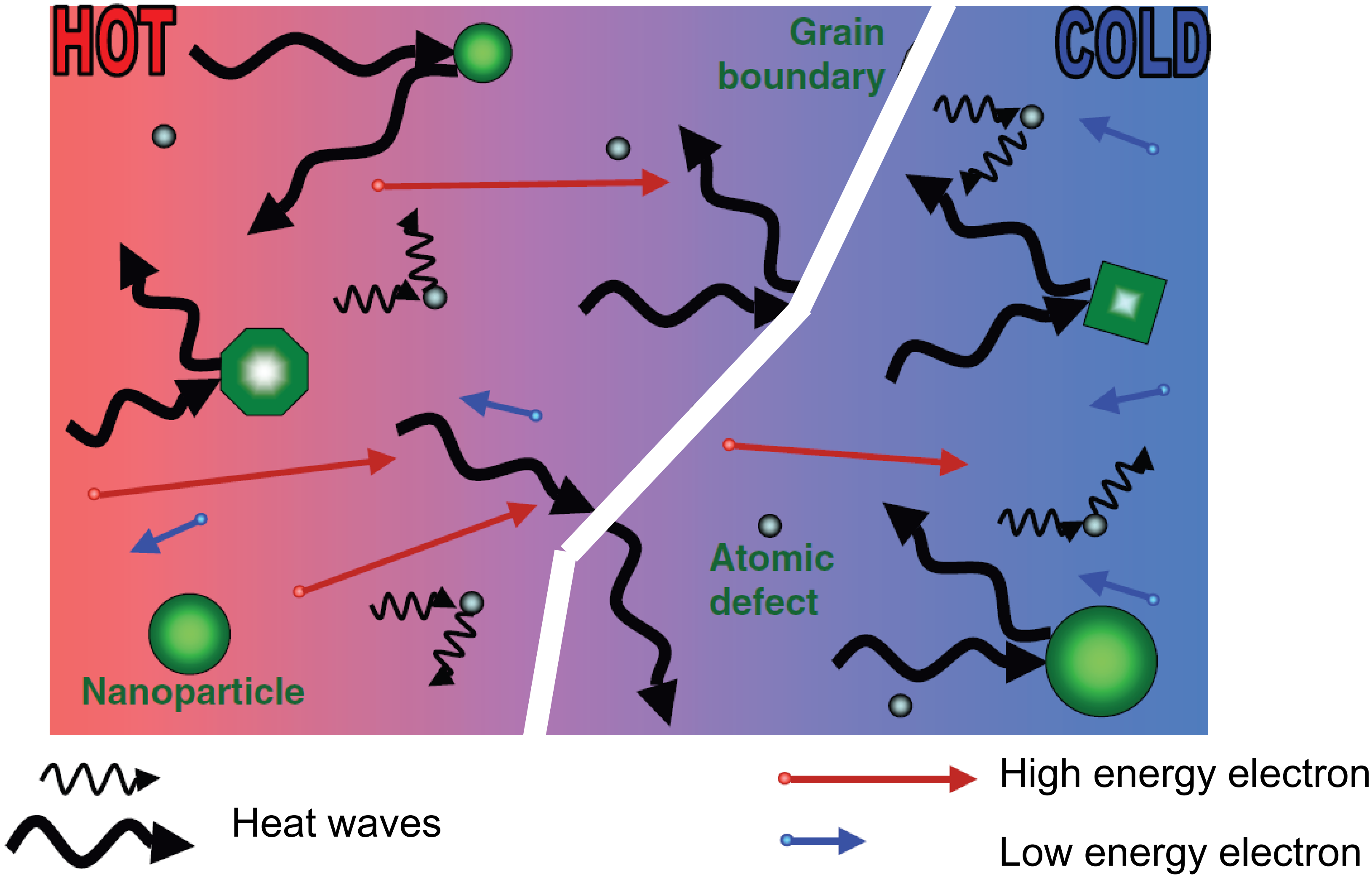
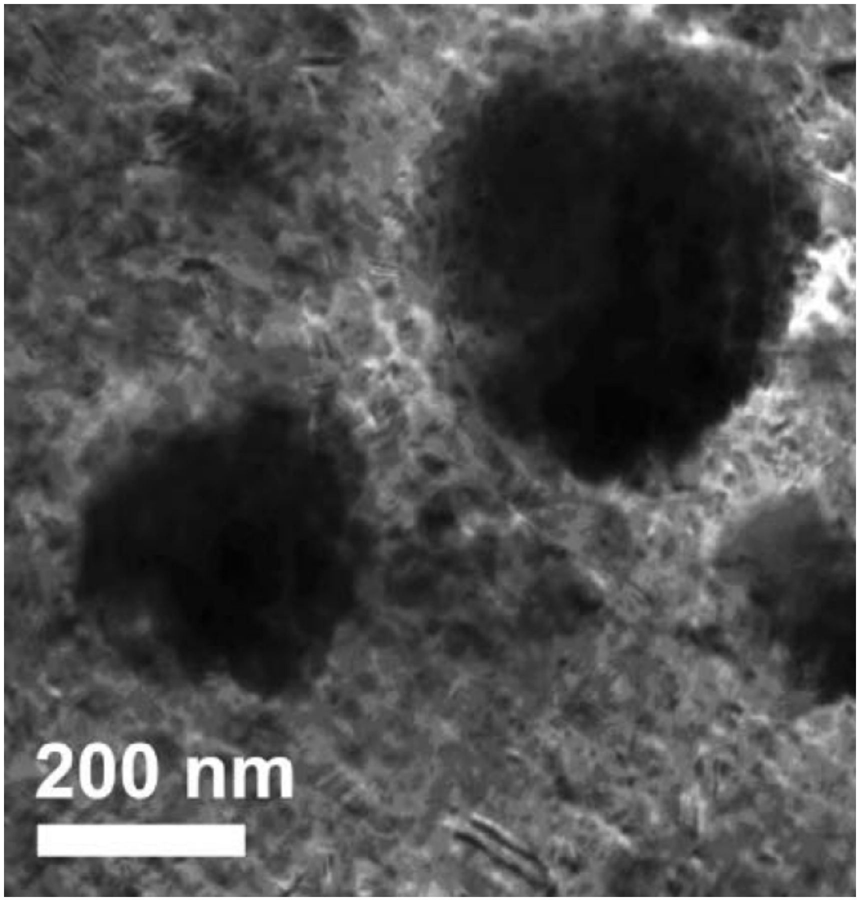
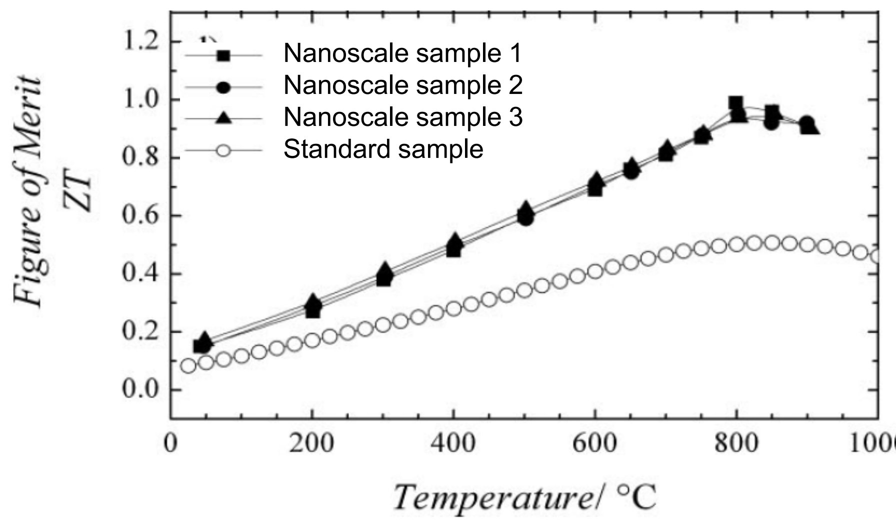


Image taken from: Vineis, C. J., Shakouri, A., Majumdar, A., & Kanatzidis, M. G. (2010 *Advanced materials*, *22*(36), 3970-80.

Experiments show nanoscale materials have higher ZT





Joshi, G., Lee, H., Lan, Y., Wang, X., Zhu, G., Wang, D., Gould, R. W., et al. (2008). *Nano letters*, *8*(12), 4670-4.

Thermoelectric fan

Thermoelectric power generation based on Seebeck effect

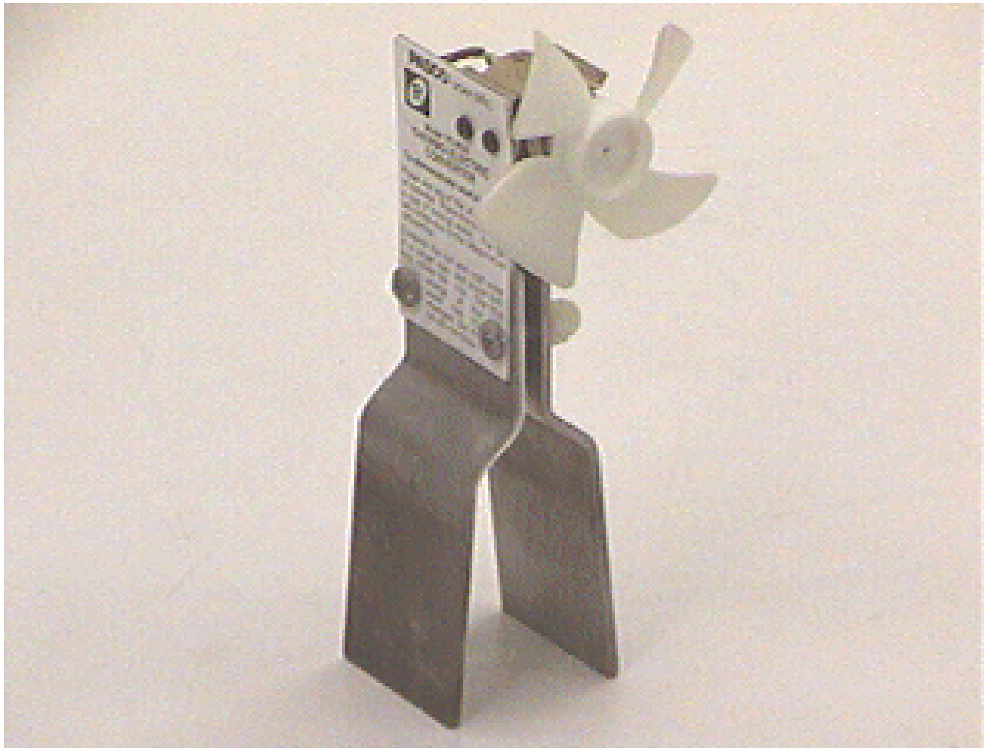


Image : Model TD-8550 Thermoelectric Converter, Pasco Scientific Co., Hayward, CA.
Stanislaw Bednarek, Thermoelectric motor, AJP 63, 1051-1052 (1995).

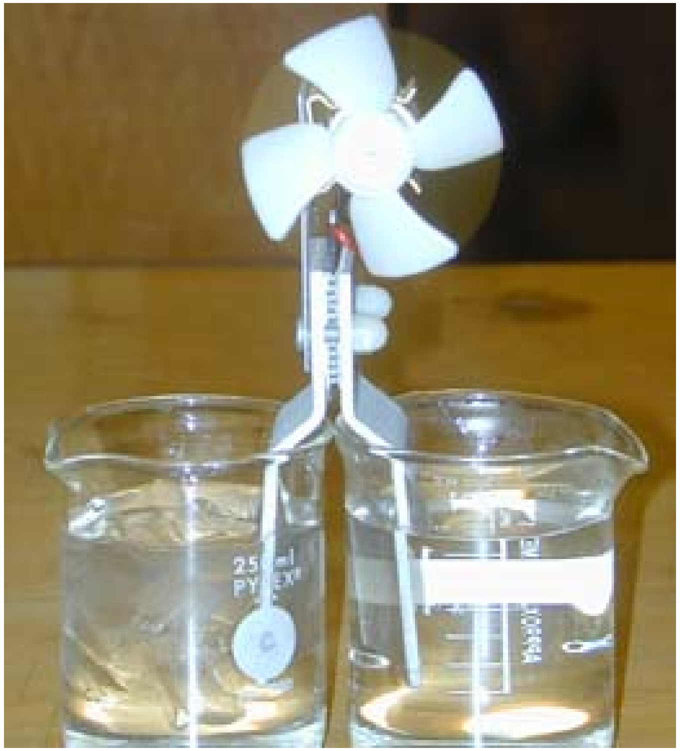
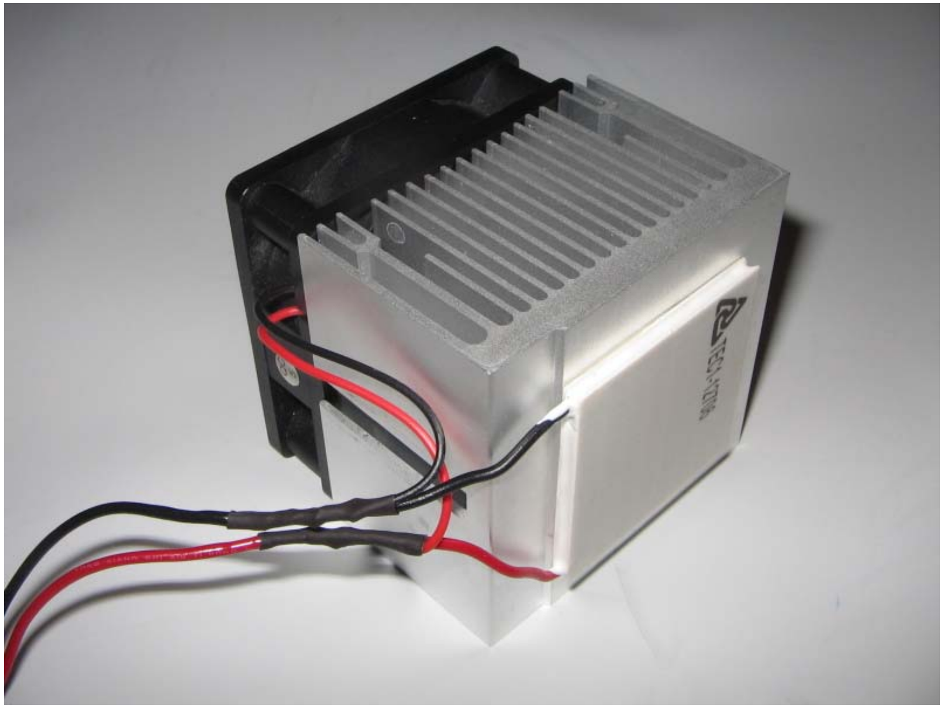


Image URL :
http://physics.sierracollege.edu/DemoRoom/Thermodynamics/4F%20Entropy%20and%20the%20Second%20Law/4f30_02.htm

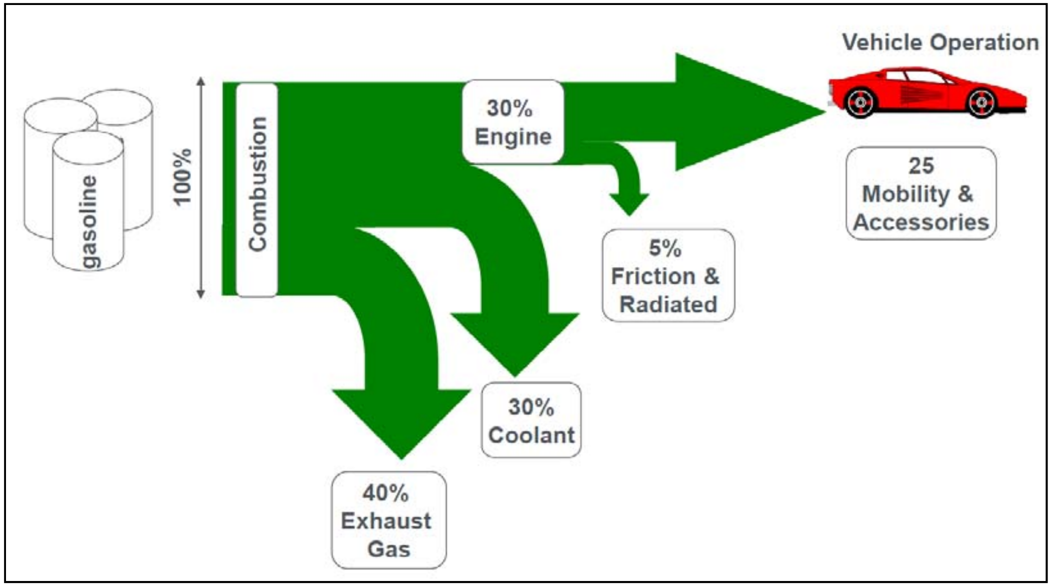
Thermoelectric cooler

Peltier cooling effect

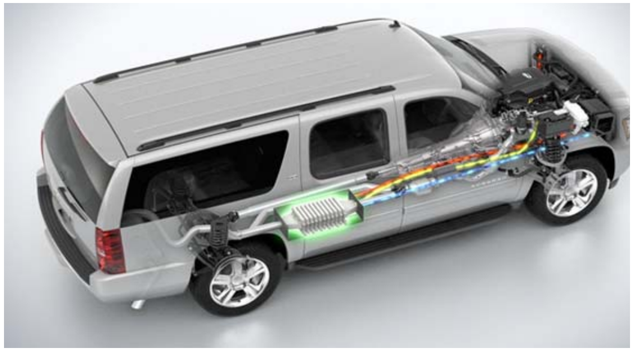


Images taken from : http://www.wholesale-electrical-electronics.com/p-thermoelectric-cooler-1462472.html (URL)

Waste Heat Recovery Systems



40% is wasted through exhaust gas



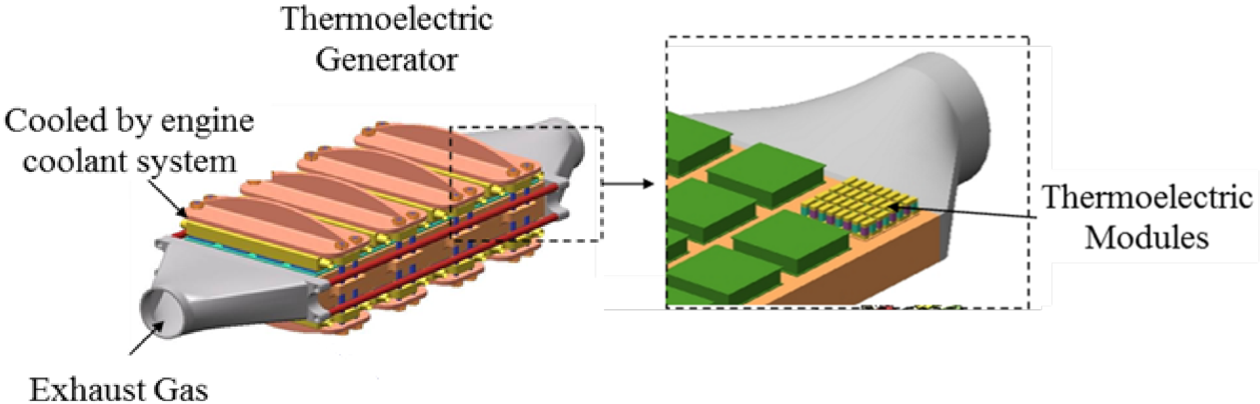


Illustration of the location of a thermoelectric generator in a vehicle

Image taken from: Fairbanks J.W., "Vehicular Thermoelectrics: A New Green Technology", DEER (2001), Michigan

Thermoelectric Generators in Automobiles

Image taken from: Fairbanks J.W., “Vehicular Thermoelectrics: A New Green Technology”, DEER (2001), Michigan

Photovoltaics:
converting sunlight into electricity

Caleb Miskin
Solar Research Group
6/15/12

How long have humans used solar energy

?

Since the beginning…

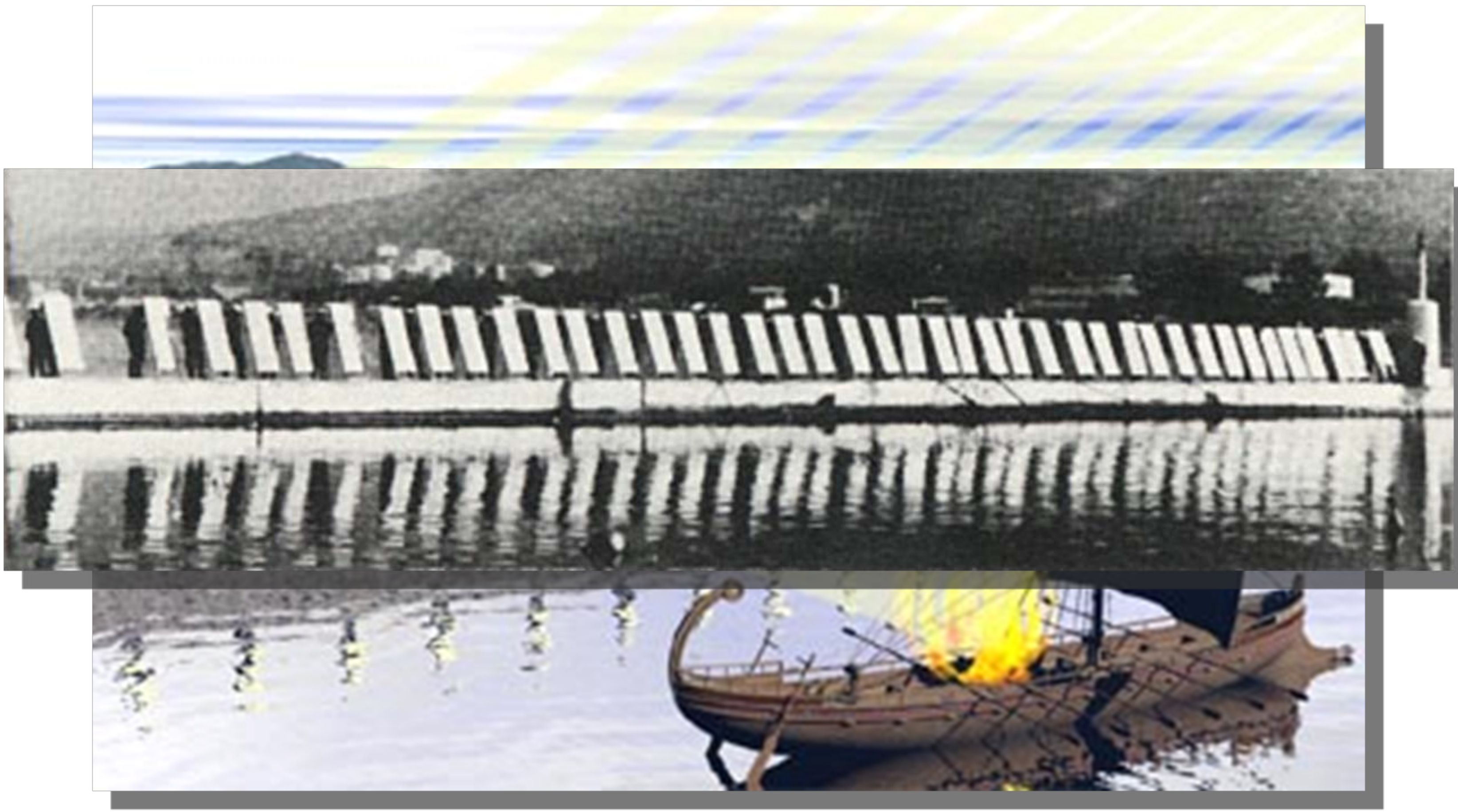
7th Century BC

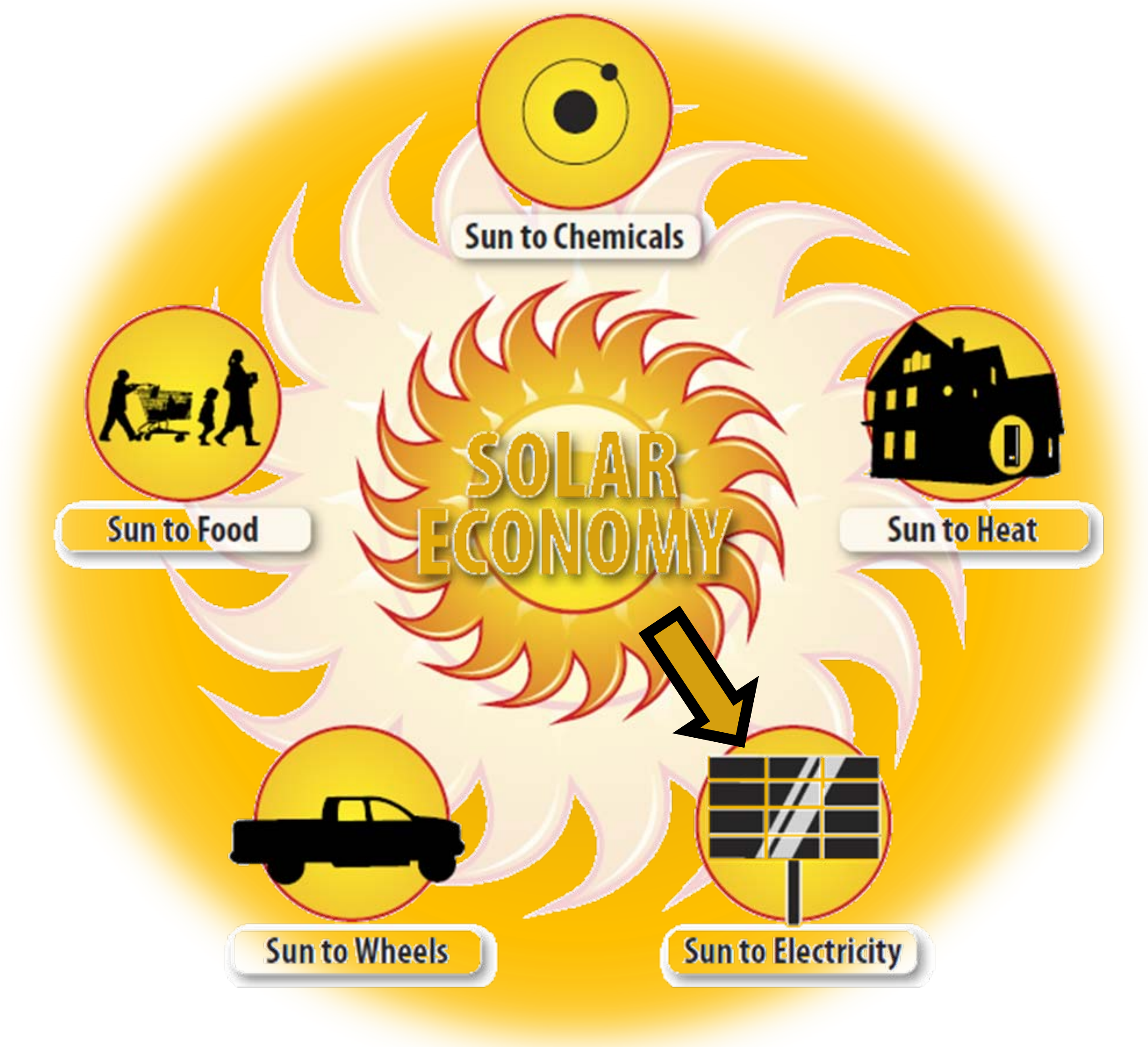
3^{rd} Century BC

Romans used parabolic mirrors to light torches

2nd Century BC

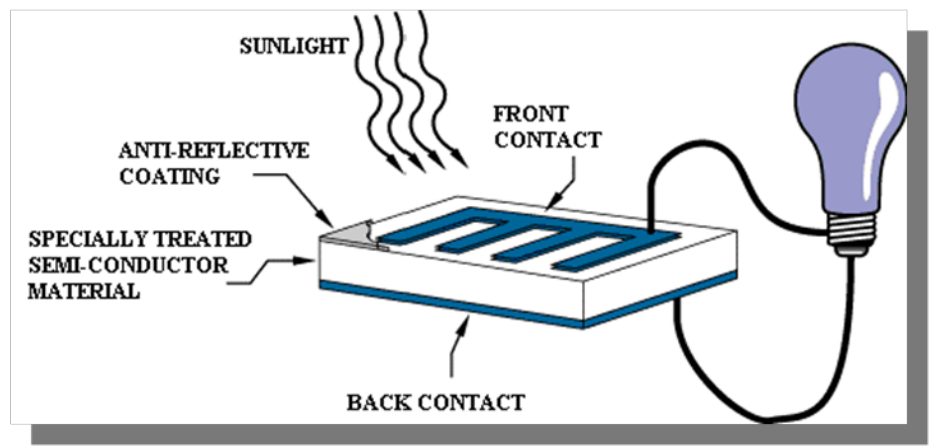
Legend of Archimedes: “The Death Ray”




Sun to Chemicals
Sun to Food
SOLAR ECONOMY
Sun to Heat
Sun to Wheels
Sun to Electricity

What is Photovoltaics (PV)?

- The direct conversion of sunlight to electricity using semiconductors



History of Photovoltaics

- 1883: Charles Fritz coated Se with Au.
- 1954: Silicon solar cell invented at Bell Labs

Benefits of PV

- The ultimate renewable resource
- Abundant
  - More energy from the sun reaches the earth in an hour than humans use in an entire year!
- Requires less land than mining fossil fuels
- Clean
- Improved national security

How much area is needed?

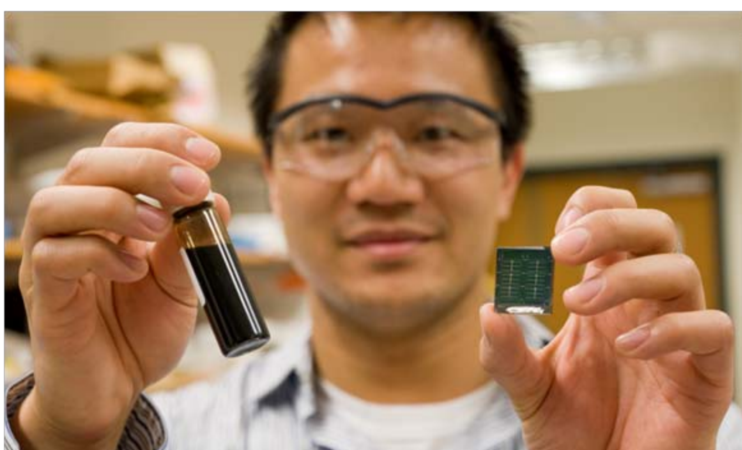
Prof. Nate Lewis (CalTech)

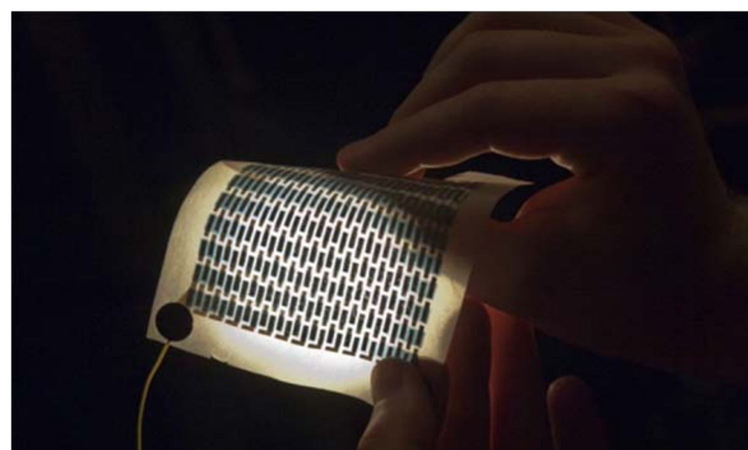
Challenges

- Cost: Oil and coal are still cheaper
  - Manufacturing and materials can be very expensive
- Storage: Need to be able to store the energy for use during the night and on cloudy days
- Toxic waste
  - Many cells contain toxic chemicals
  - Need for robust recycling programs

Purdue takes on the challenge

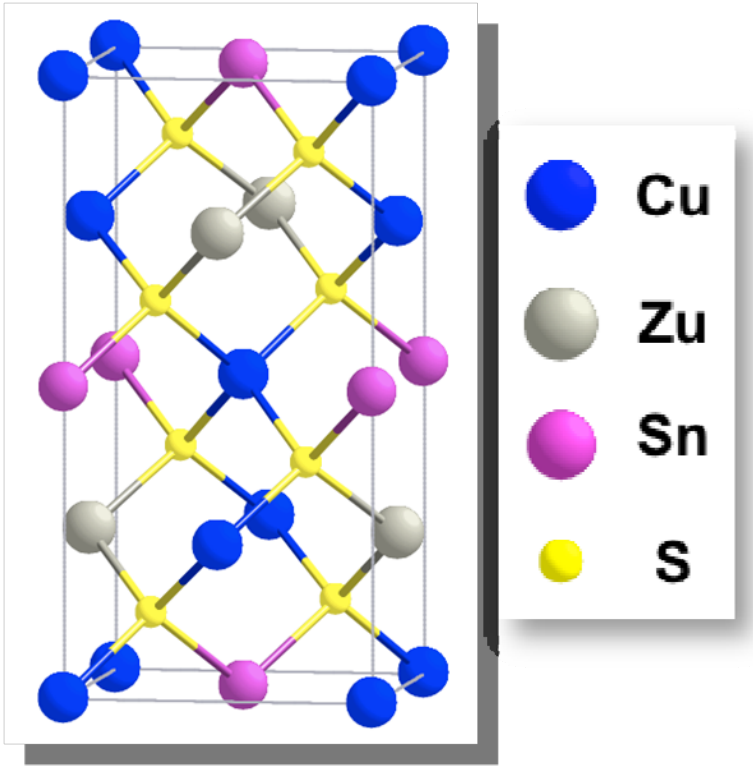
- Thin-film solar cells from nanocrystal inks using earth-abundant materials
  - Lower material costs
  - Possibility for inexpensive printable solar cells
  - Flexible for use everywhere



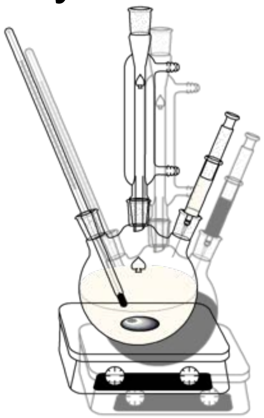


A Novel Material

- Copper Zinc Tin Sulfide/Selenide (CZTSSe)
  - $Cu_2ZnSnS_ySe_{1-y}$
- All materials are relatively cheap, abundant, and less toxic than current PV cells
- Efficiency as high as 10% and improving quickly

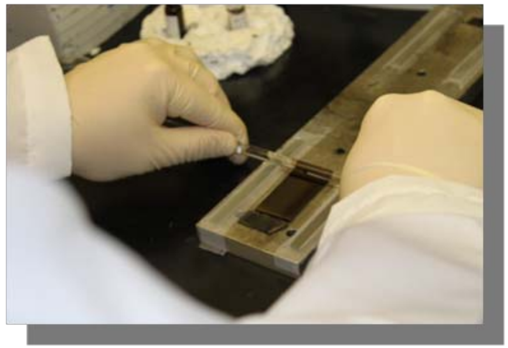


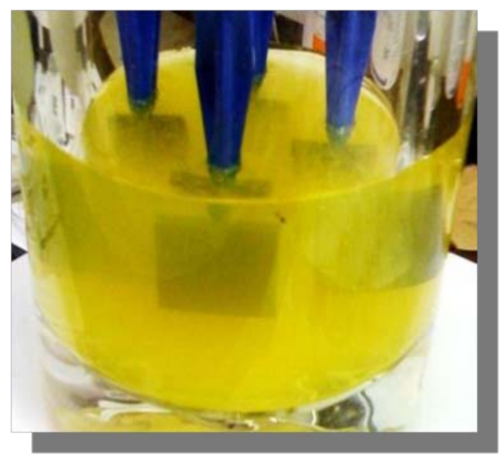
Nanocrystal synthesis



Ink Formulation

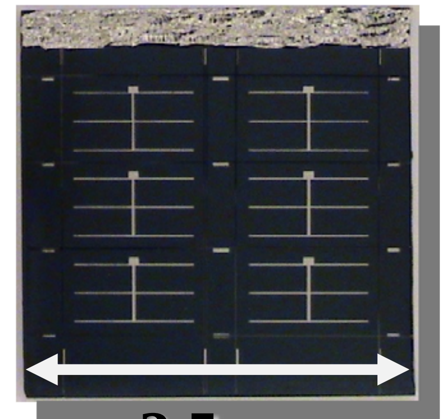
Film coating





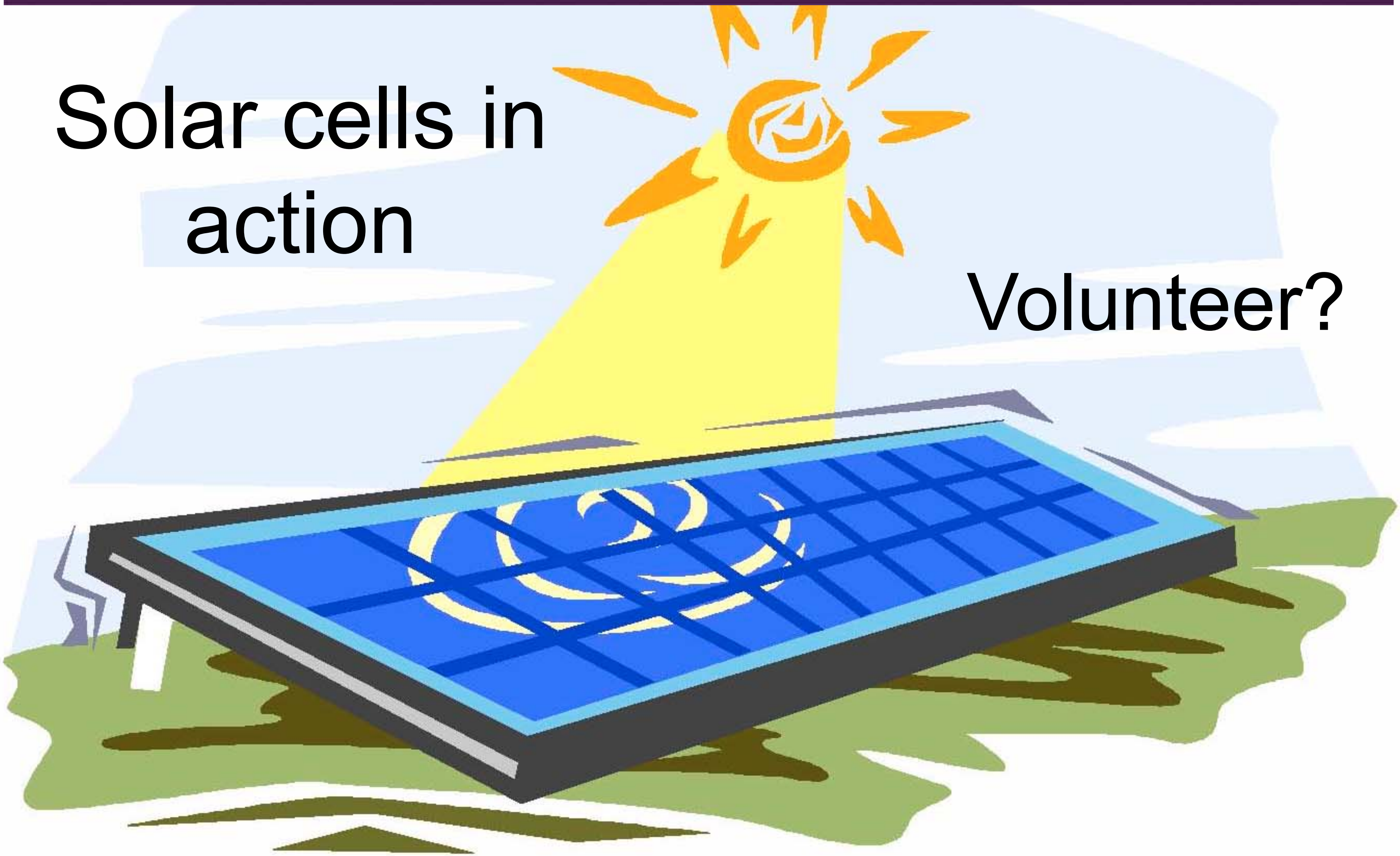
Further Processing

Finished Device



2.5 cm

Solar cells in action



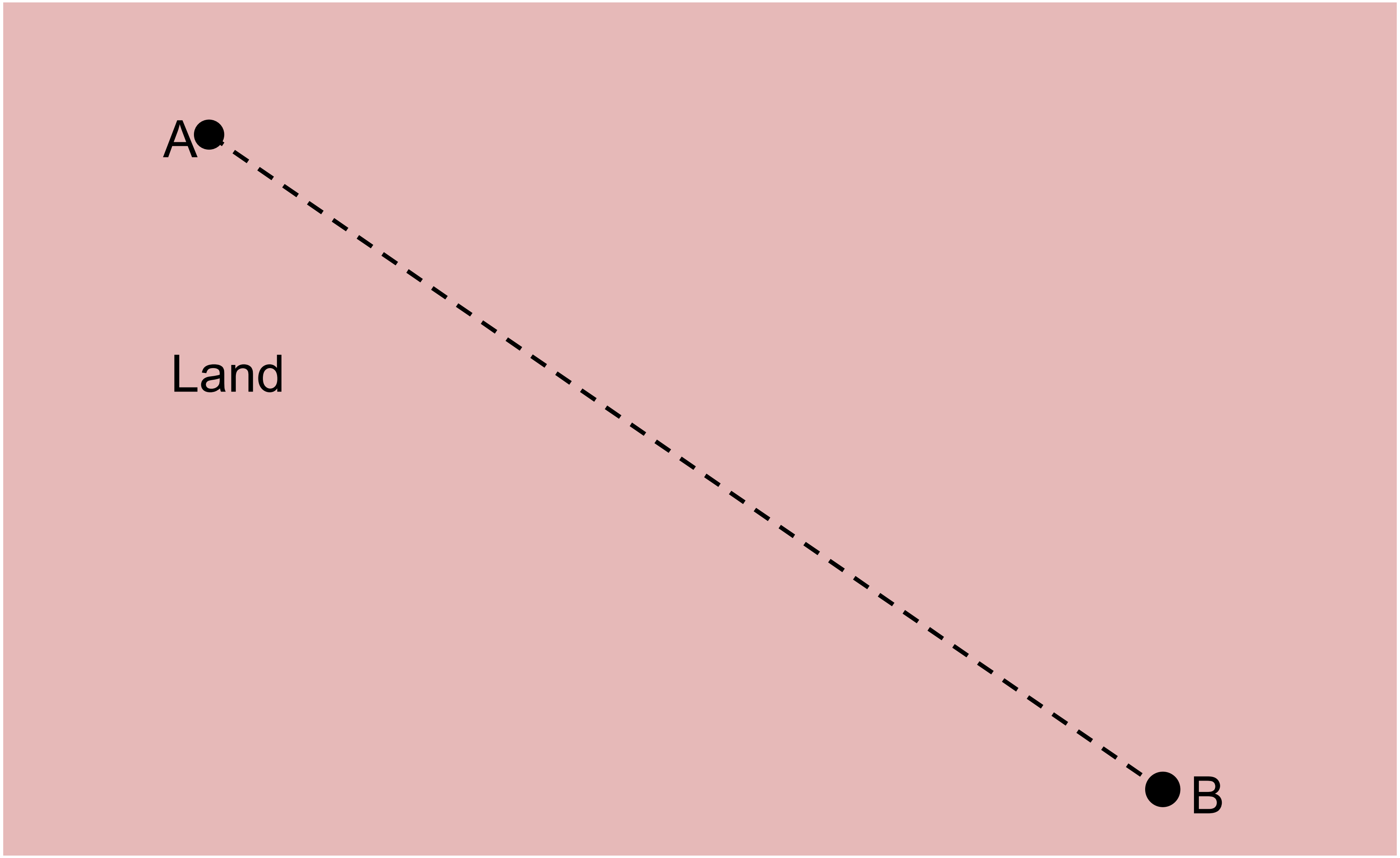
Volunteer?

Controlling Refractive Index for Improving Photovoltaic Light Collection

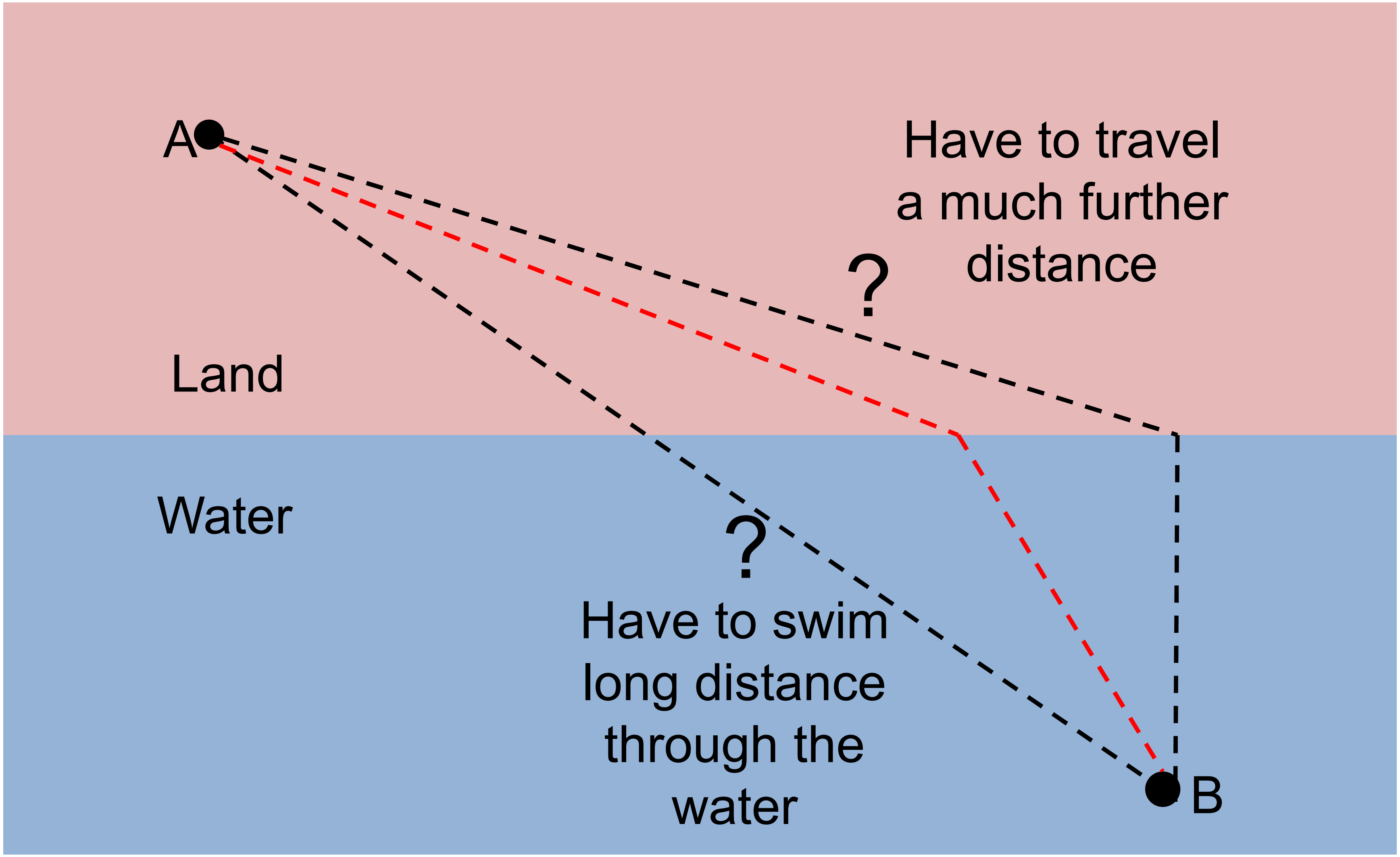
Professor Alexandra Boltasseva
Paul R. West

06/15/2012

Find the Path of Shortest Time



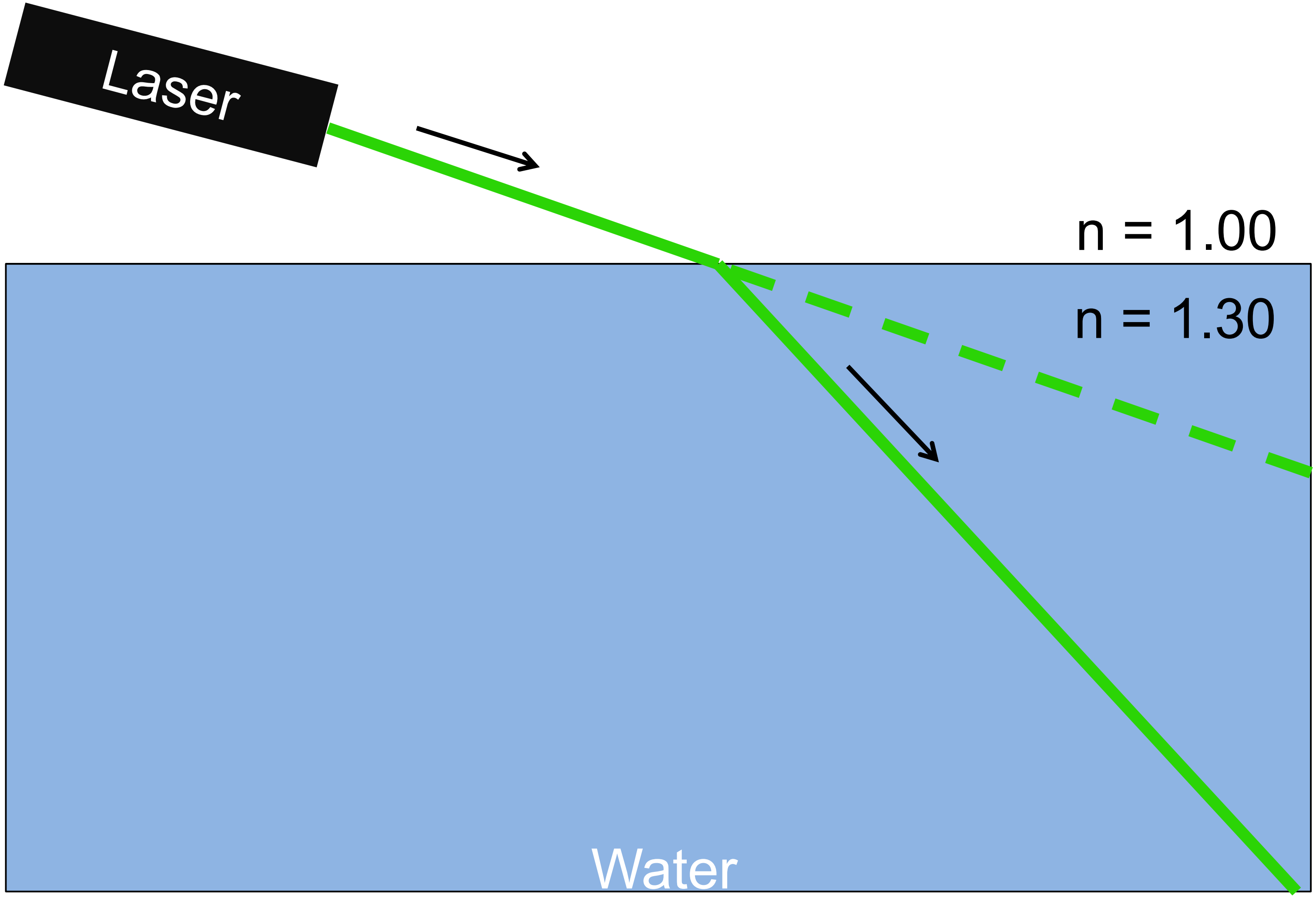
Find the Path of Shortest Time



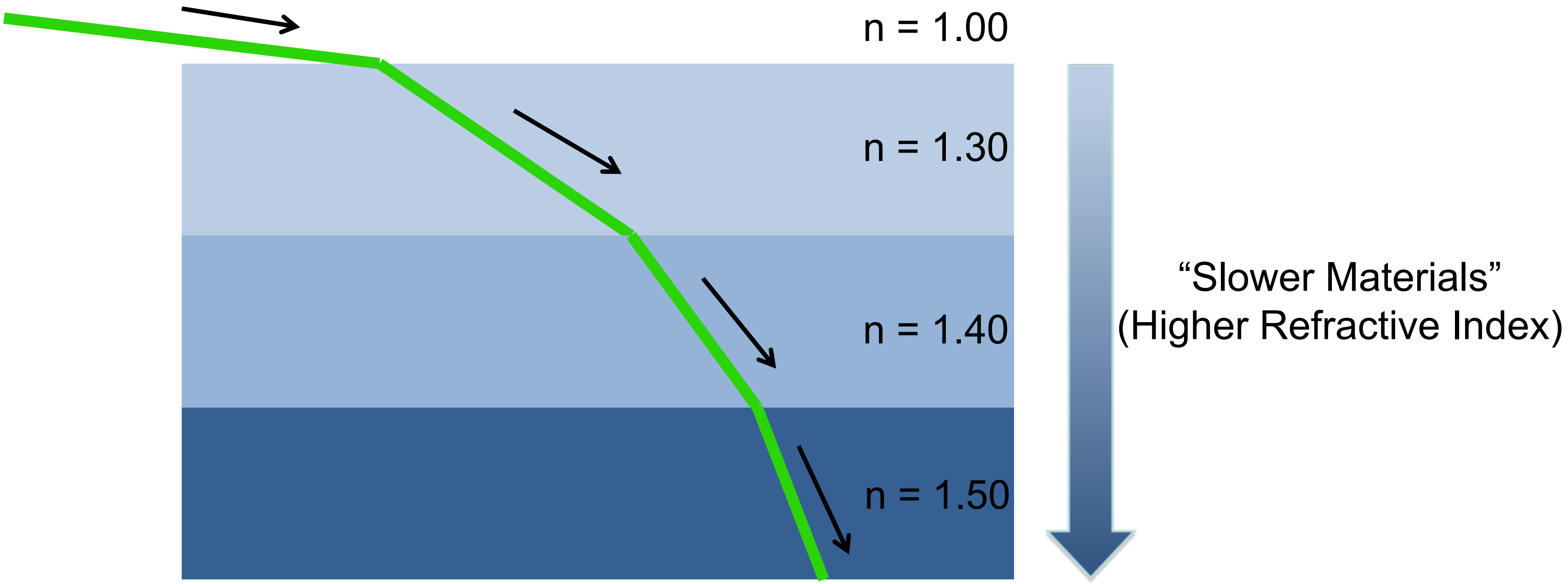
Characteristics of Light

- Light travels at the *ultimate speed limit* of the universe 300,000,000 m/s or 671,000,000 mph through space
- Light travels more slowly in any other material (glass, water, etc.)
- The amount that light is slowed in these materials is called the material's "refractive index"
- Example: Glass has a refractive index of 1.5. This means that through glass, light travels 300,000,000/1.5 or 200,000,000 m/s
- Because light will always take the path of least time, it will always bend inward into these materials

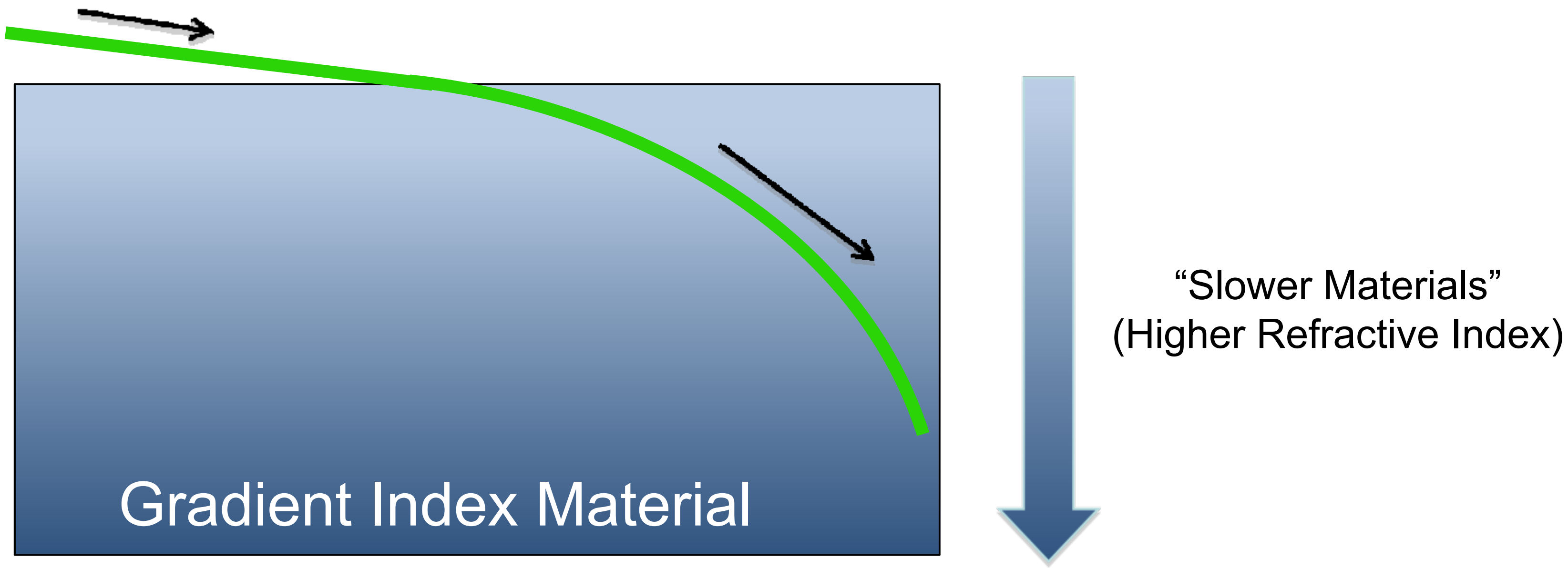
Refractive Index Demo



Gradient Refractive Index Demo



Gradient Refractive Index Demo

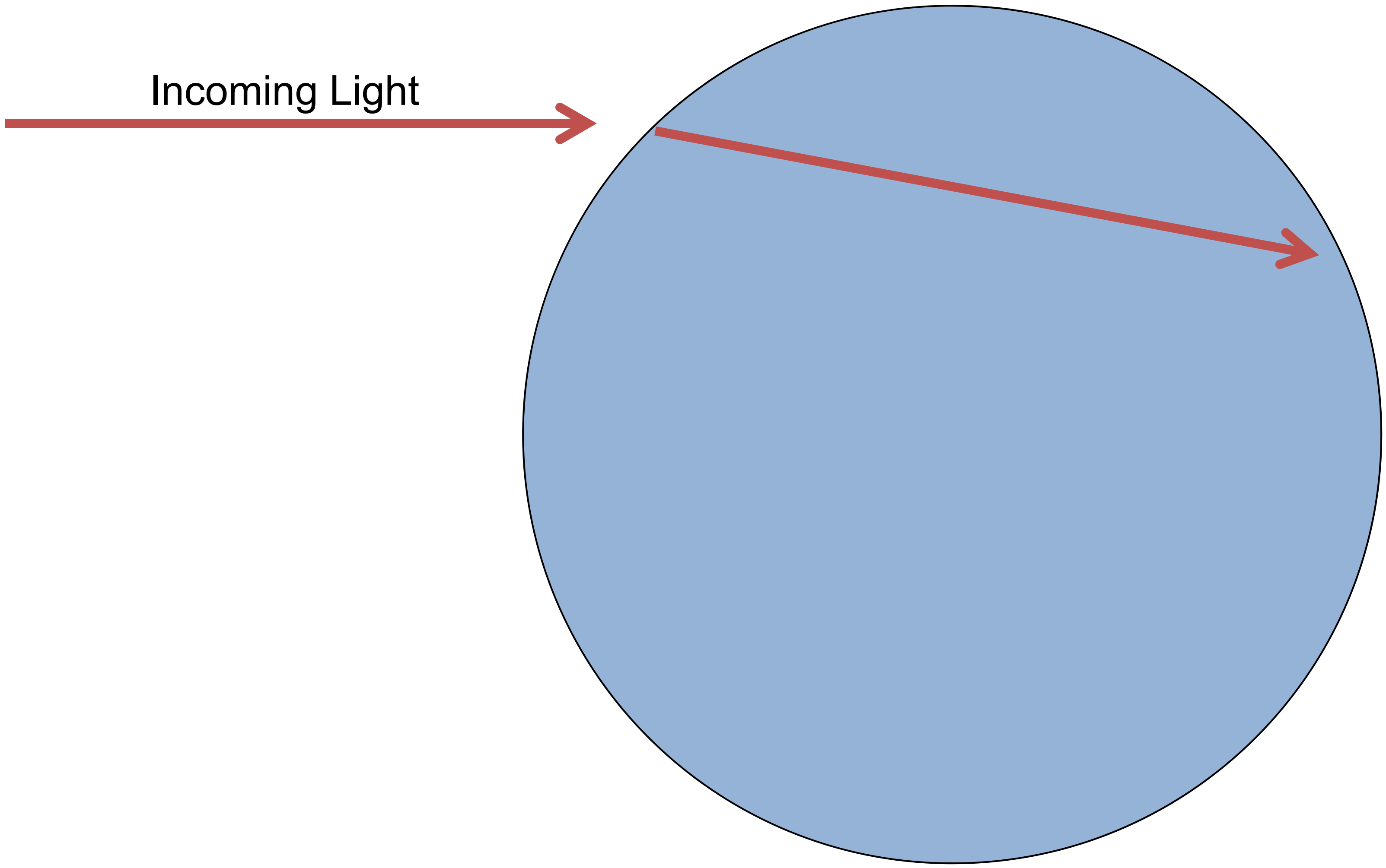


http://www.youtube.com/watch?v=A7xKDxM_LEk

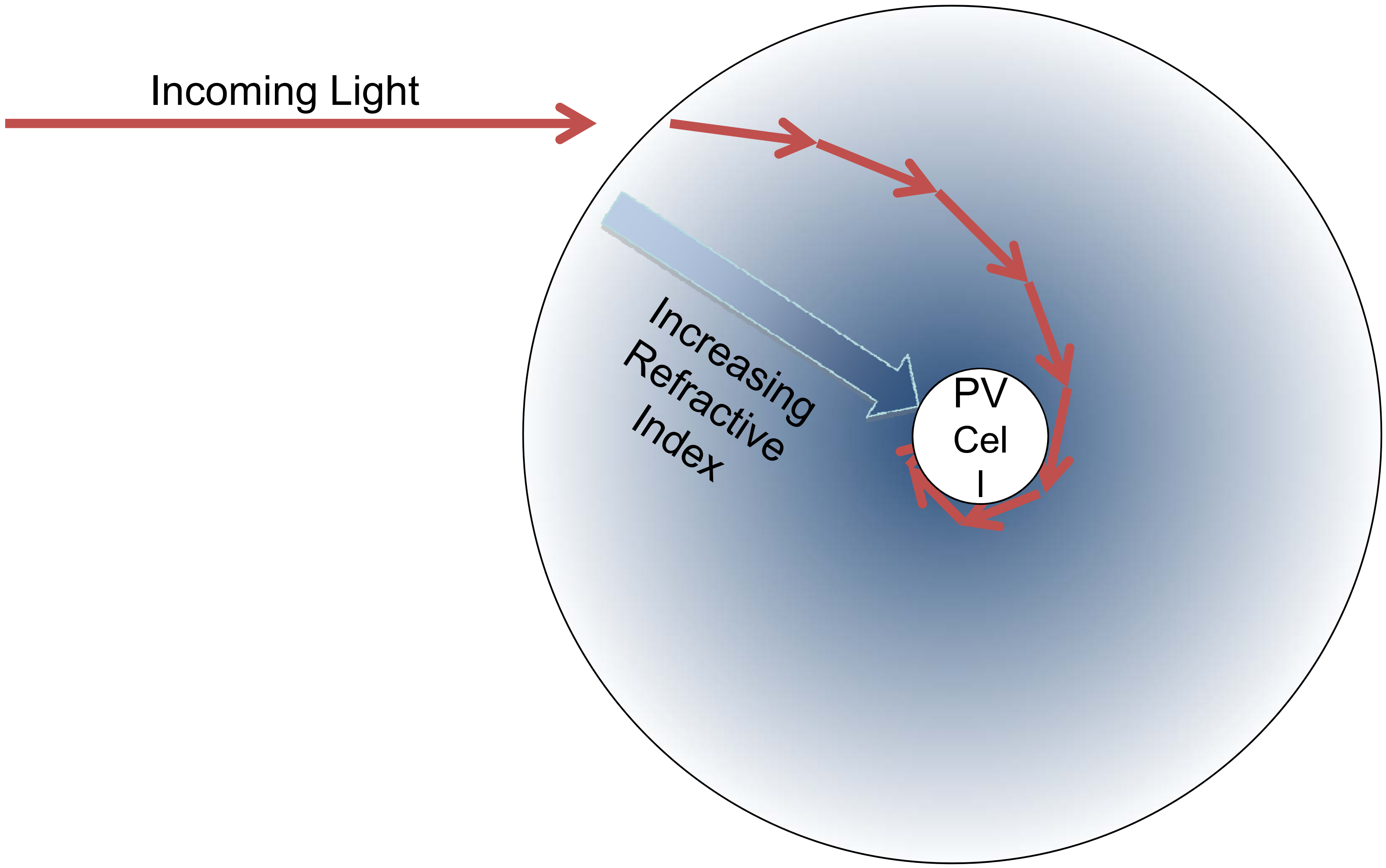
Metamaterials

- Using Nanotechnology, we are able to create materials of almost any refractive index (including negative index!)
- We can also create materials with optical properties that are beyond anything that can be found in nature
- The greek word for “beyond” is “meta”, therefore we call these materials “metamaterials”
- Using metamaterials, we can create devices including invisibility cloaks and optical black holes

Optical Black Holes



Optical Black Holes



Thank You!

Questions?