# Thermoelectrics 101

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# Outline

**1) Fundamentals**

2) Applications

3) Final Remarks

# Definition and Usage

**ther·mo·e·lec·tric**

/ˌTHərmō-iˈlektrik/

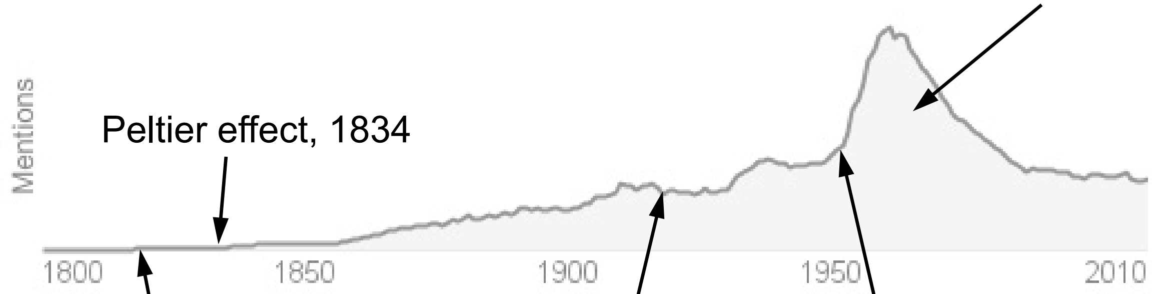
*adjective*

adjective: **thermoelectric**

producing electricity by a difference of temperatures.

Translate thermoelectric to Choose language

Use over time for: thermoelectric

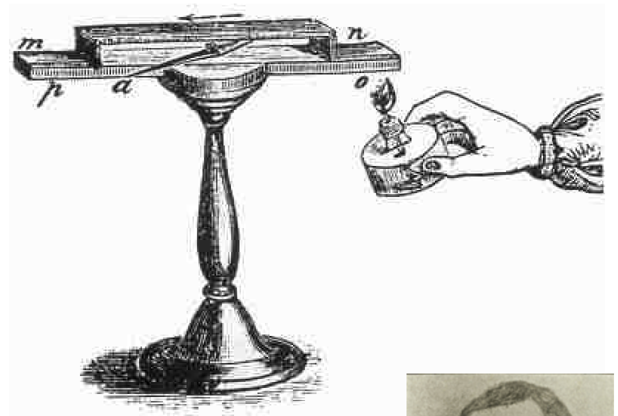


# Seebeck vs. Peltier

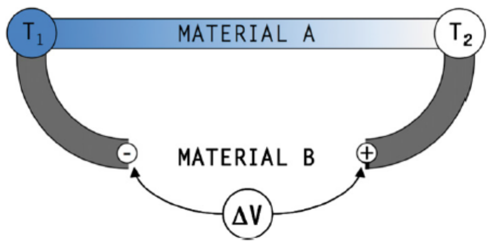
- Seebeck effect (1821):
  - Loop of Cu and Bi wires (thermocouple)
  - Heating one end deflected magnetic needle, initial confused with thermomagnetism
  - Ørsted (1823) correctly explained that **electric flow occurred due to temperature gradient**

$$\Delta V \equiv (S_B - S_A)\Delta T$$

  - $S_{A,B}$ = Seebeck coefficient = thermopower specific to material A or B (units of μV/K)
  - Ex: $\Delta S \sim 300$ μV/K and $\Delta T = 100$ K, we generate 30 mV
  - *Q: how do we generate 1.5 V like AA battery?*

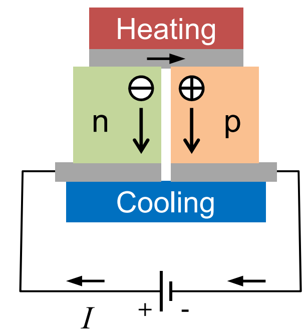



Thomas Seebeck



# Seebeck vs. Peltier

- Peltier effect (1834):
  - Opposite of Seebeck effect
  - **Electric current flow through a junction of materials A and B can be used to heat or cool**




$$Q \equiv \Pi_{AB} I = (S_B - S_A) T I$$

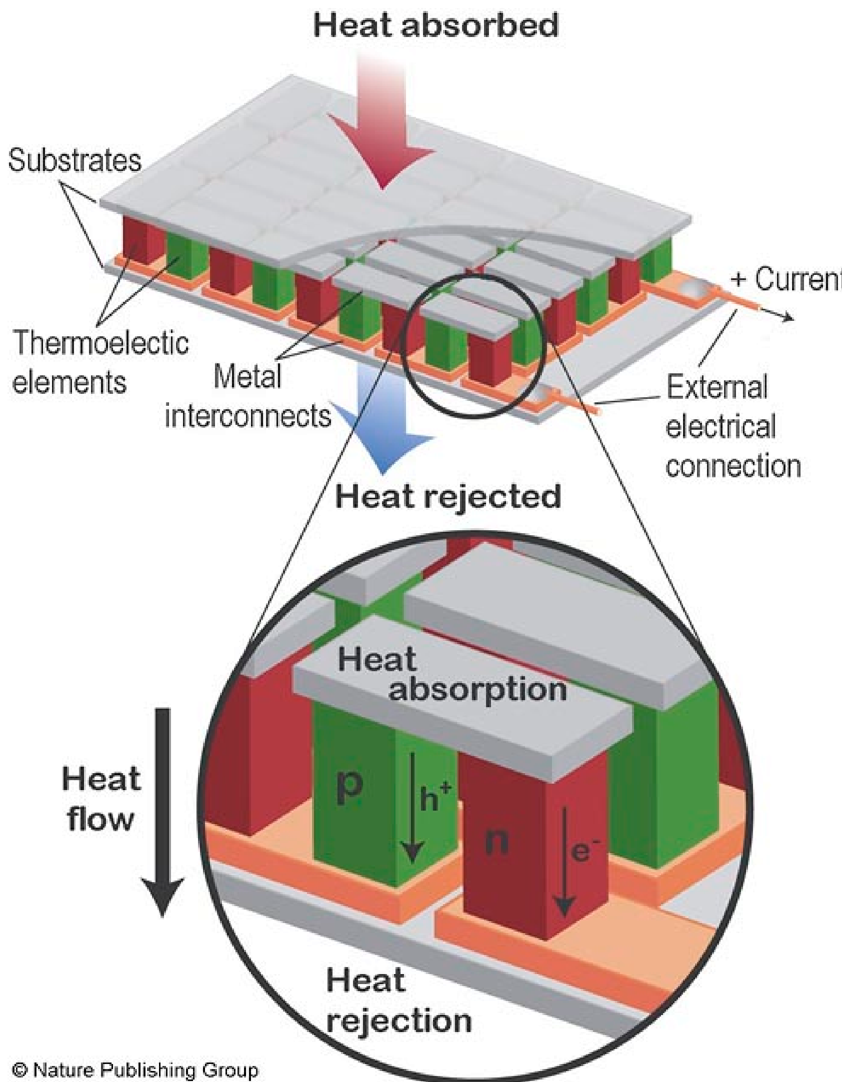
  - $\Pi_{AB} = S_{AB}T$ = Peltier coefficient of junction
  - Heating and cooling are reversible, depending on the direction (± sign) of the current *I*
  - Ex: I = 1 mA, $\Delta S \sim 300\ \mu V/K$ and T = 300 K gives us cooling power of 90 μW
  - *Q: how do we generate greater cooling (or heating) power?*

Jean Peltier

# Answer (Look Ahead)

- Commercial TE modules are typically arranged in a series of alternating “n” and “p”-doped semiconductor legs

- TE legs are “electrically in series” and “thermally in parallel”

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Jeff Snyder, Caltech

# Seebeck vs. Peltier vs. Thomson Effect

- Thomson effect (1851):
  - *Continuous* version of Seebeck effect, no junction needed
  - Gradual change in S (∇S) due to temperature variation (∇T) inside a material creates local electric field (∇V) and local heating or cooling (Q)

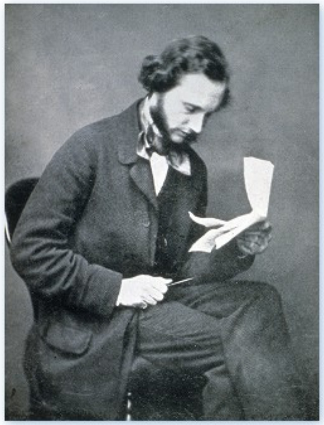
$$\nabla V = T\nabla S$$

$$Q = T\mathbf{J} \cdot \nabla \mathbf{S}$$

current density
($A/m^2$)

  - Thomson effect directly measurable in one material
  - Peltier and Seebeck more easily measurable for pairs of materials

  - Seebeck, Peltier, Thomson effects are *reversible*
  - Joule heating ($I^2R$) is *not* reversible



William Thomson
(Lord Kelvin)

# Combining TE, Joule & Heat Flow

- Electric field:

$$\mathbf{E} = -\nabla V = \frac{\mathbf{J}}{\sigma} + S\nabla T$$

Ohm Seebeck

- Heat flux:

$$Q'' = -k\nabla T + STJ$$

- Local current density:

$$\mathbf{J} = \sigma\left(-\nabla V - S\nabla T\right)$$

- Heat diffusion equation with Seebeck effects and Joule heating

$$-Q''' = \nabla\cdot\left(k\nabla T\right) + \mathbf{J}\cdot\mathbf{E} - T\mathbf{J}\cdot\nabla S$$

# Common Seebeck Coefficients

| Material | Seebeck coefficient S *relative to platinum* (μV/K) |
|---|---|
| Selenium | 900 |
| Tellurium | 500 |
| Silicon | 440 |
| Germanium | 330 |
| Antimony | 47 |
| Nichrome | 25 |
| Molybdenum | 10 |
| Cadmium, tungsten | 7.5 |
| Gold, silver, copper | 6.5 |
| Rhodium | 6.0 |
| Tantalum | 4.5 |
| Lead | 4.0 |
| Aluminium | 3.5 |
| Carbon | 3.0 |
| Mercury | 0.6 |
| Platinum | 0 (definition) |
| Sodium | -2.0 |
| Potassium | -9.0 |
| Nickel | -15 |
| Constantan | -35 |
| Bismuth | -72 |

semiconductors tend to have high |S|, but magnitude and sign depend on doping ($S_p > 0$ and $S_n < 0$)

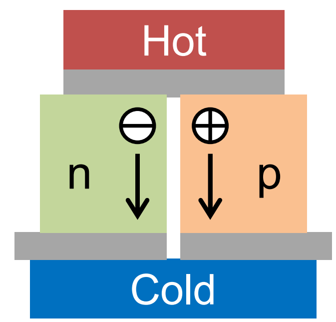
metals tend to have low S

Thomas Seebeck's original junction

source: Wikipedia

# What Is the Microscopic Origin of TE?

- Seebeck = electrons (or holes*) diffuse in a temperature gradient, leading to $\Delta V$
  - Diffusion from hot to cold → like hot air molecules ($O_2$, $N_2$) diffusing from space heater to farthest corners of the room
  - Kinetic energy → $(3/2)k_BT \approx (1/2)mv^2$ → $v = (3k_BT/m)^{1/2}$
  - Hotter electrons (or holes) are faster, but they also carry charge, which sets up the voltage gradient




- Peltier = electrons (or holes*) carry kinetic energy (in addition to charge) as they move with current flow
  - Explains why we prefer materials with higher σ (electrical conductivity), i.e. metals or highly doped semiconductors

*hole = missing electron in a material = broken bond

# Seebeck Coefficient (Classical & Metals)

- Seebeck coefficient can be thought of as the heat per carrier per degree K (specific heat per carrier), $S \approx C/q$
- In classical electron gas (recall $k_B/q$ = 86 μV/K):

$$S_{classic} \approx \frac{3}{2}\frac{k_B}{q} \approx 130\,\mu\mathrm{V/K}$$

- In normal metals only small fraction around $E_F$ contribute, so the thermopower is very small:

$$S_{metal} \approx \left(\frac{k_B T}{E_F}\right)\frac{k_B}{q} \approx 1\,\mu\mathrm{V/K}$$

- In semiconductors, energy carriers can be "far" from $E_F$, so the thermopower can be large:

$$S_{semi} \approx \left|\frac{E - E_F}{qT}\right| \approx 1\,\mathrm{mV/K}$$

# Seebeck Coefficient (In General)

- Keeping track of particle motion (Boltzmann transport equation)

$$\mathbf{v}\cdot\nabla_{\mathbf{r}} f + \frac{q\mathbf{F}}{\hbar}\cdot\nabla_{\mathbf{k}} f = -\frac{f(\mathbf{r},\mathbf{k}) - f_{\text{eq}}(\mathbf{r},\mathbf{k})}{\tau(\mathbf{k})}$$

- Where

$$f_{\text{eq}} = \frac{1}{1+\exp\dfrac{E-E_F}{k_B T}}$$

- The electrical conductivity and Seebeck coefficient are:

$$\sigma = \int \sigma(E)dE$$

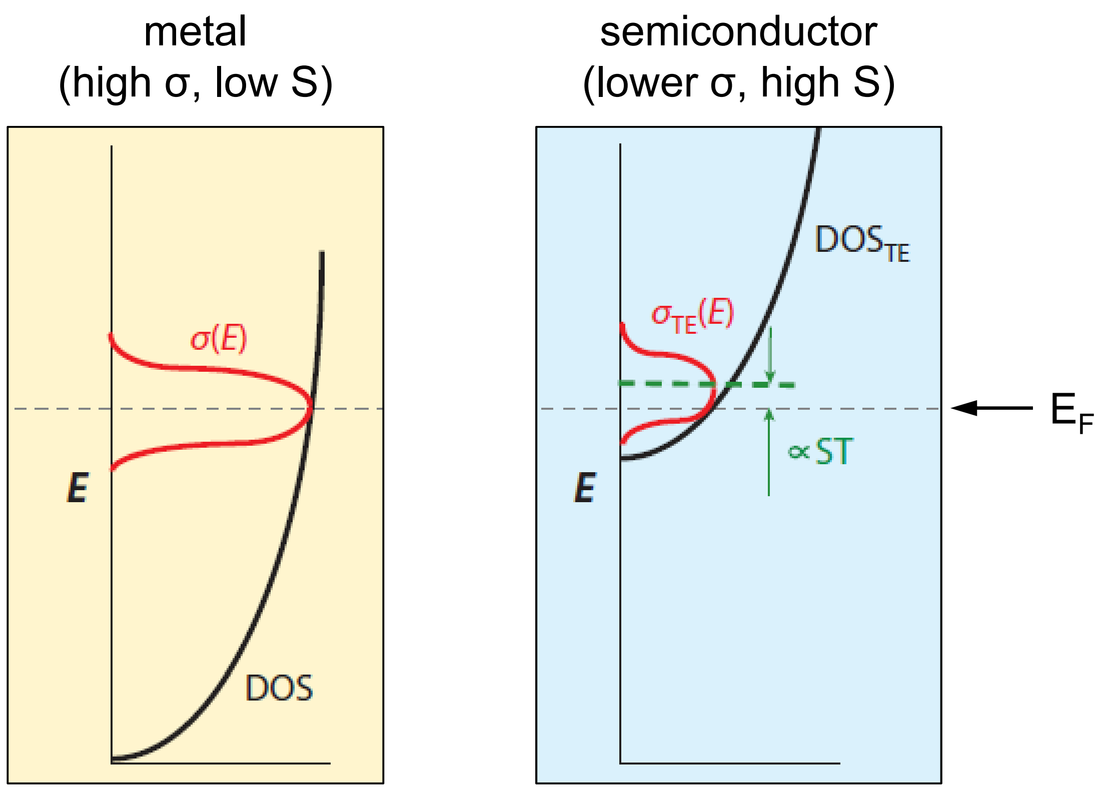
$$S = \frac{1}{qT}\frac{\int (E-E_F)\sigma(E)dE}{\int \sigma(E)dE}$$

- Where the *differential* conductivity

$$\sigma(E) = q^2\tau(E)v^2(E)D(E)\left(-\frac{\partial f_{\text{eq}}}{\partial E}\right)$$

density of states (DOS)

# Picturing the Transport "Window"

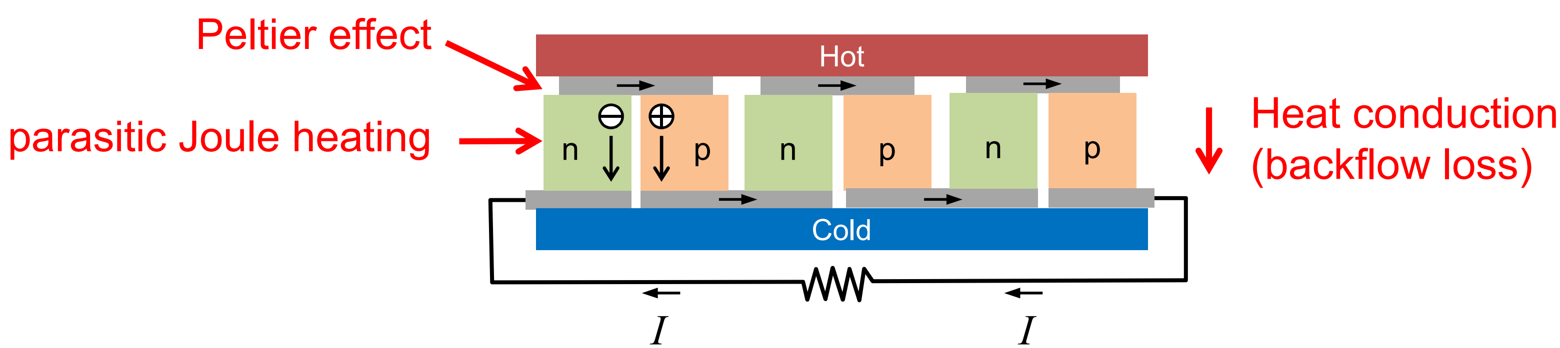



- In metals, density of states (DOS) does not vary sharply around $E_F$
- In doped semiconductors, $E_F$ is at band edge where DOS varies sharply (ex: in *n*-type semiconductor, more states available for transport above than below $E_F$) → **for high S, need asymmetric DOS near $E_F$**

Shakouri, *Annu. Rev. Mater. Res.* (2011)

# Thermoelectric Figure of Merit (ZT)

- How efficient are TEs?




Obtain highest

$$Q = STI - I^2\left(\frac{L}{\sigma A}\right) - \frac{kA\Delta T}{L}$$

Peltier    Joule loss    Heat backflow

When maximizing

$$\boxed{ZT = \frac{S^2\sigma T}{k}}$$

$k_e + k_L$

# Thermoelectric Figure of Merit (ZT)

- How efficient are TEs?
- Figure of merit:

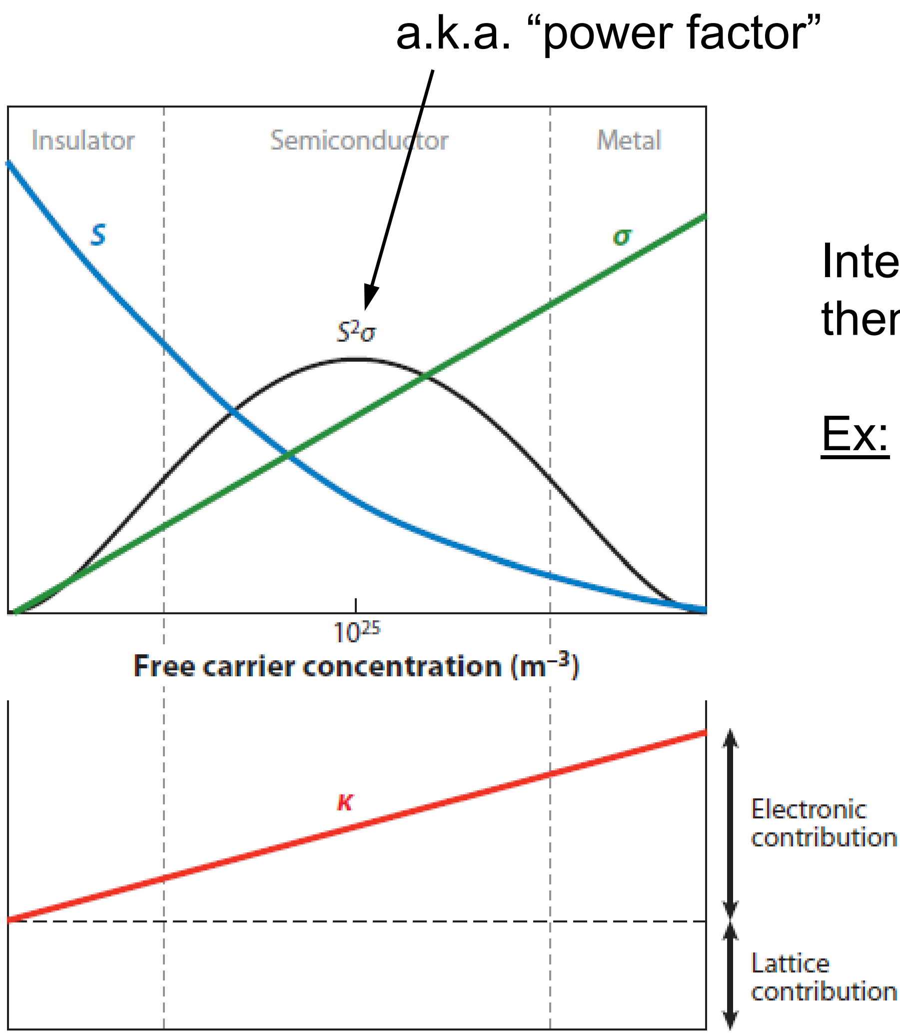
$$ZT = \frac{S^2 \sigma T}{k}$$

$k_e + k_L$

- Thus, **one must simultaneously maximize S and σ (electrical conductivity) while minimizing k (thermal conductivity)**

- These quantities are inter-related, such that increasing S typically leads to decreasing σ
- Also, $k = k_e + k_L$, thermal conductivity is sum of electron and lattice (phonon) contributions, so increasing σ leads to increasing $k_e \leftrightarrow$ Wiedemann-Franz-Lorenz (WFL) law

# Trade-Offs in Maximizing ZT




Interesting: if $k_L = 0$ (hypothetically) then $(ZT)_{max} = S^2/L_0$

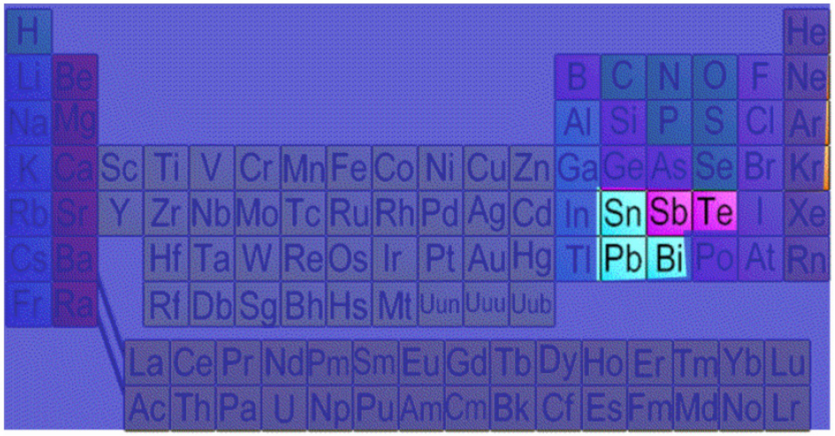
<u>Ex:</u> if S = 300 μV/K then $(ZT)_{max}$ = 3.7

$$k_e = L_0 T \sigma \qquad \text{(WFL)}$$

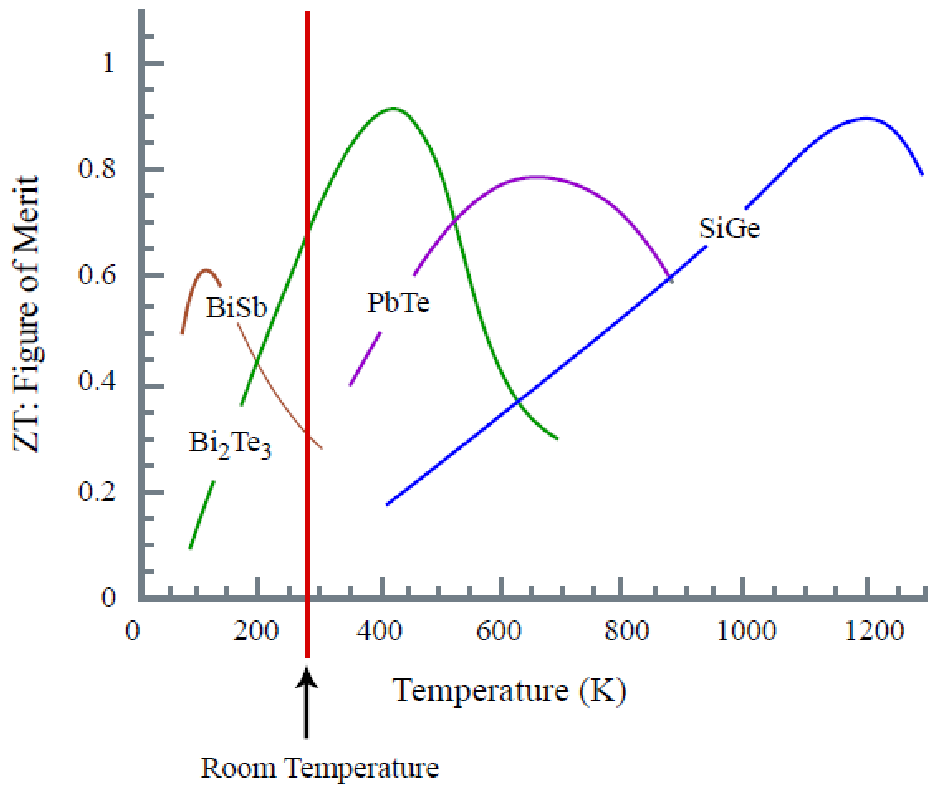
$k_L$ must be minimized

Lorenz constant $L_0 = 2.45 \times 10^{-8}$ $W\Omega/K^2$

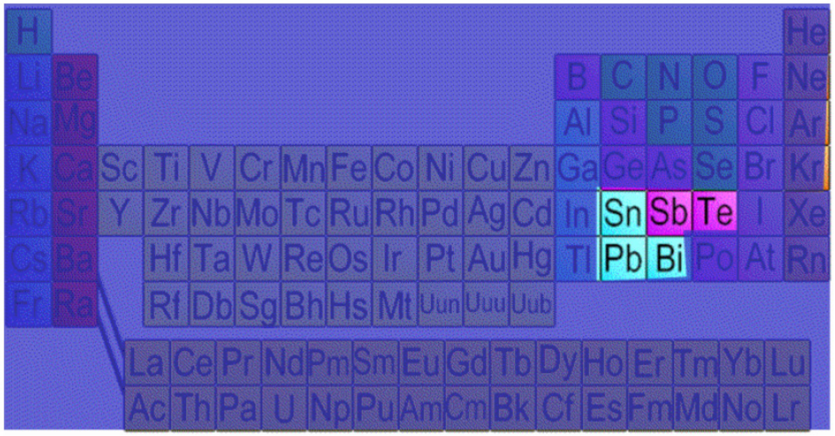
# ZT for Commercial Materials




- 0.6 < ZT < 1 for commercially available materials over 300-1200 K temperature range
- Note different materials are best at different temperatures

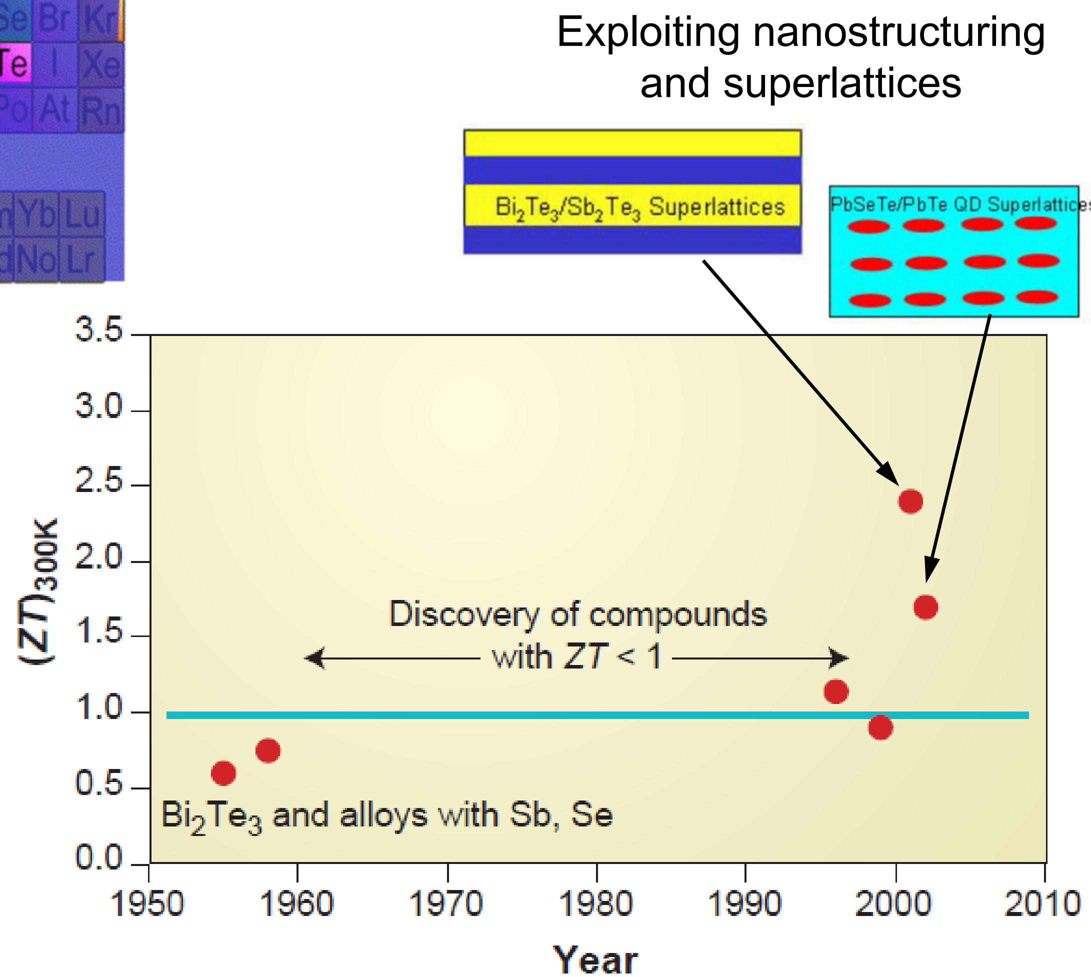


# Evolution of ZT over Time



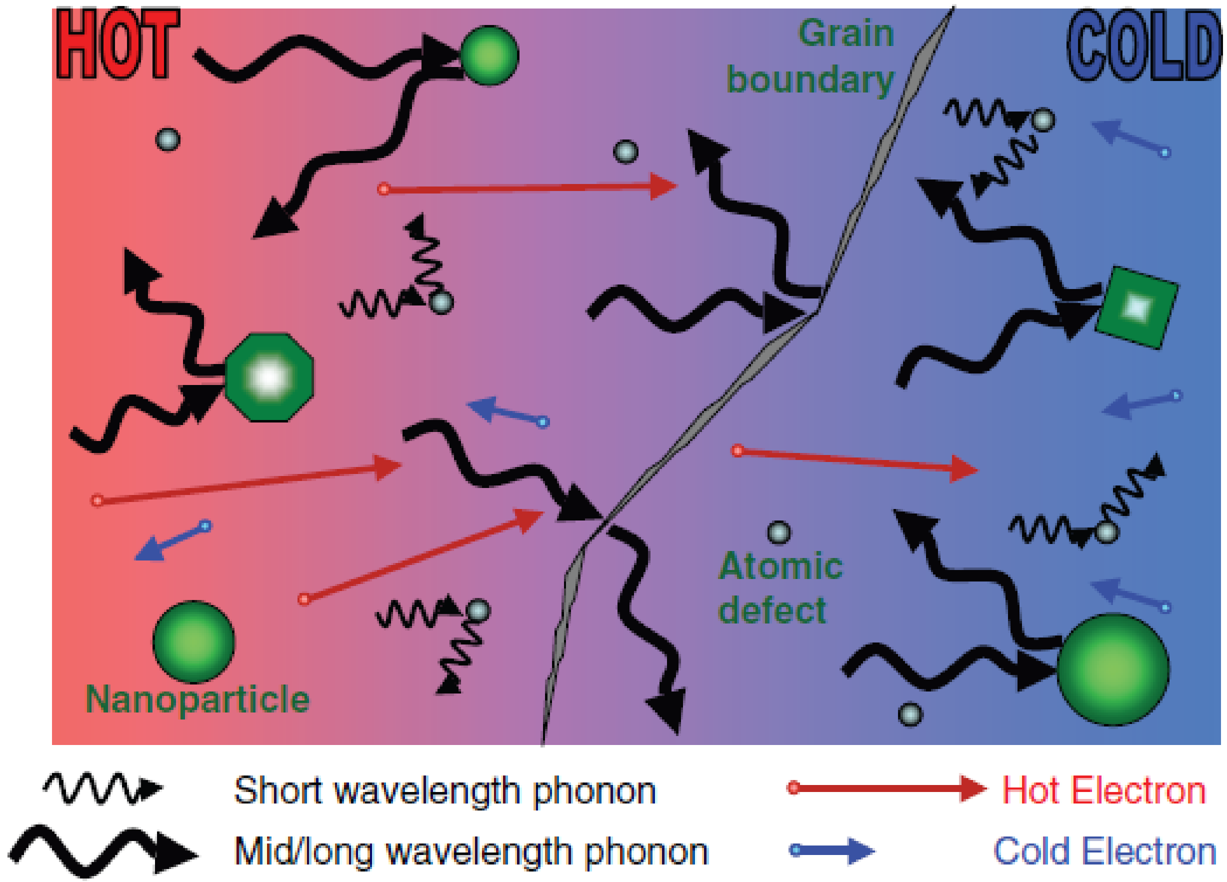

Over ~5 decades ZT has been limited to ≤ 1 (at room temperature)

Improvements have often come from artificially lowering thermal $k_L$




Source: A. Majumdar, *Science* (2004)

# How Can We Lower Thermal K?



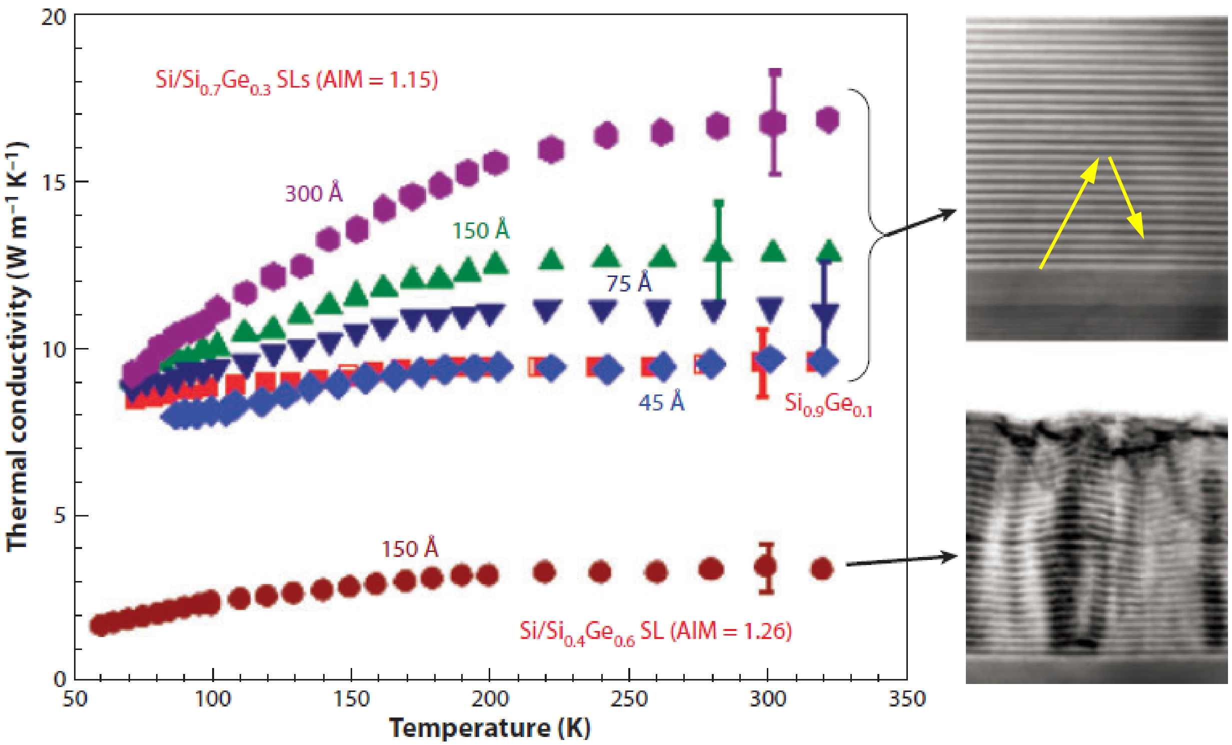

- Introduce features that scatter phonons, not electrons
- “Phonon glass, electron crystal” (G. Slack, 1960s)

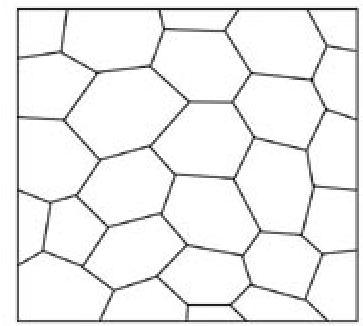
# Reducing Thermal Conductivity

- Reduce thermal $k_L$ using nanoscale scattering features

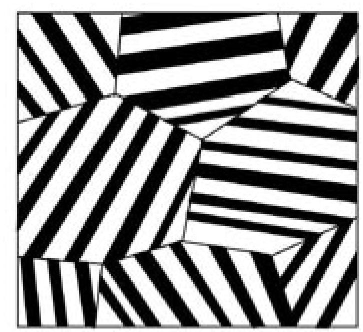
$$k_L = \frac{1}{3} C v \lambda$$

reduce mean free path by
increasing number of interfaces



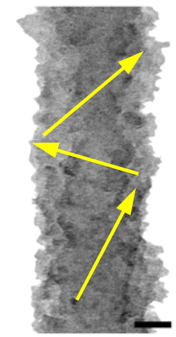
Small Grain



Lamella within Grains

# Reducing Thermal Conductivity

- Using edge roughness of Si nanowires



Vol 451|10 January 2008|**doi:10.1038/nature06381** nature

## Enhanced thermoelectric performance of rough silicon nanowires

Allon I. Hochbaum[1]*, Renkun Chen[2]*, Raul Diaz Delgado[1], Wenjie Liang[1], Erik C. Garnett[1], Mark Najarian[3], Arun Majumdar[2,3,4] & Peidong Yang[1,3,4]

PRL **102,** 125503 (2009) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2009

### Impact of Phonon-Surface Roughness Scattering on Thermal Conductivity of Thin Si Nanowires

Pierre Martin,[1,*] Zlatan Aksamija,[1] Eric Pop,[1,2,†] and Umberto Ravaioli[1]

[1]*Beckman Institute and Department of Electrical and Computer Engineering, University of Illinois, Urbana-Champaign, Urbana, Illinois 61801, USA*

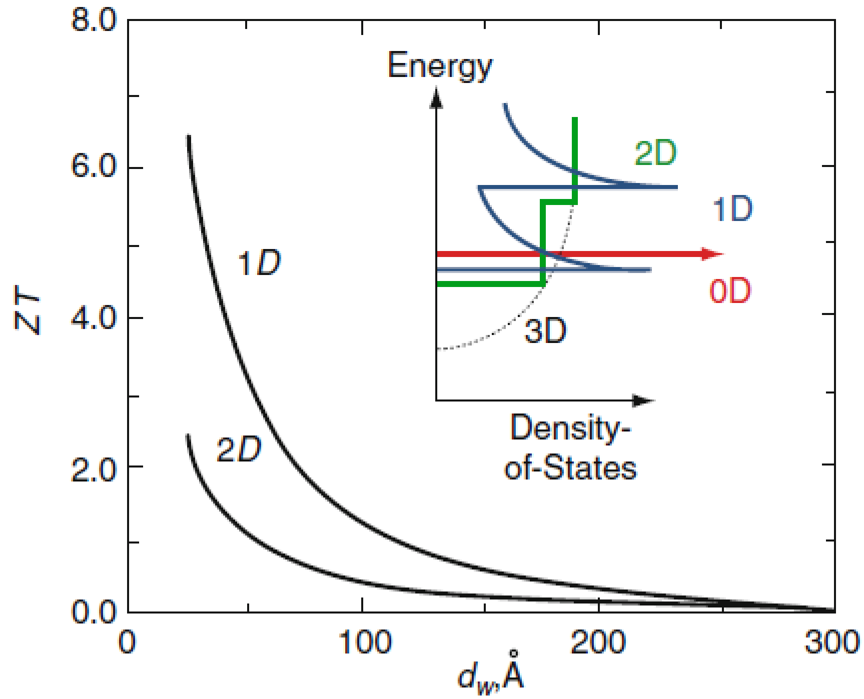
[2]*Micro- and Nano-Technology Laboratory, University of Illinois, Urbana-Champaign, Urbana, Illinois 61801, USA*

(Received 24 November 2008; published 27 March 2009)

We present a novel approach for computing the surface roughness-limited thermal conductivity of silicon nanowires with diameter $D < 100$ nm. A frequency-dependent phonon scattering rate is computed from perturbation theory and related to a description of the surface through the root-mean-square roughness height $\Delta$ and autocovariance length $L$. Using a full phonon dispersion relation, we find a quadratic dependence of thermal conductivity on diameter and roughness as $(D/\Delta)^2$. Computed results show excellent agreement with experimental data for a wide diameter and temperature range (25–350 K),

# Effects of Nanostructuring on TEs

- Hicks and Dresselhaus (1993)* pioneered concept of quantum confinement effects for TEs
- Sharp features in the 1D and 2D density of states (DOS) lead to asymmetric σ(E) and should increase S
- Challenge: sharp DOS features become "blurred" if there is size non-uniformity in the system
- Most recent breakthroughs benefitted from reduction in $k_L$




*http://dx.doi.org/10.1103/PhysRevB.47.12727

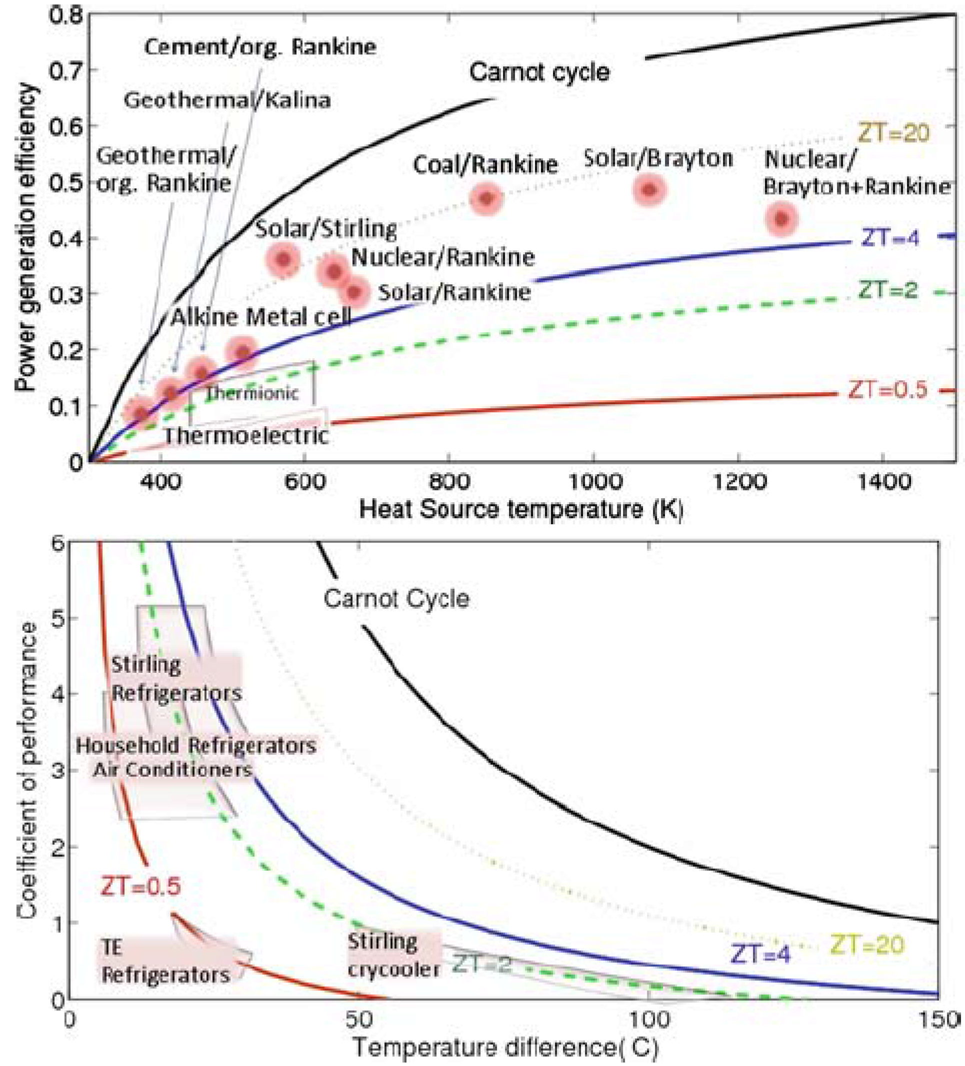
# How High ZT?

- TE efficiency

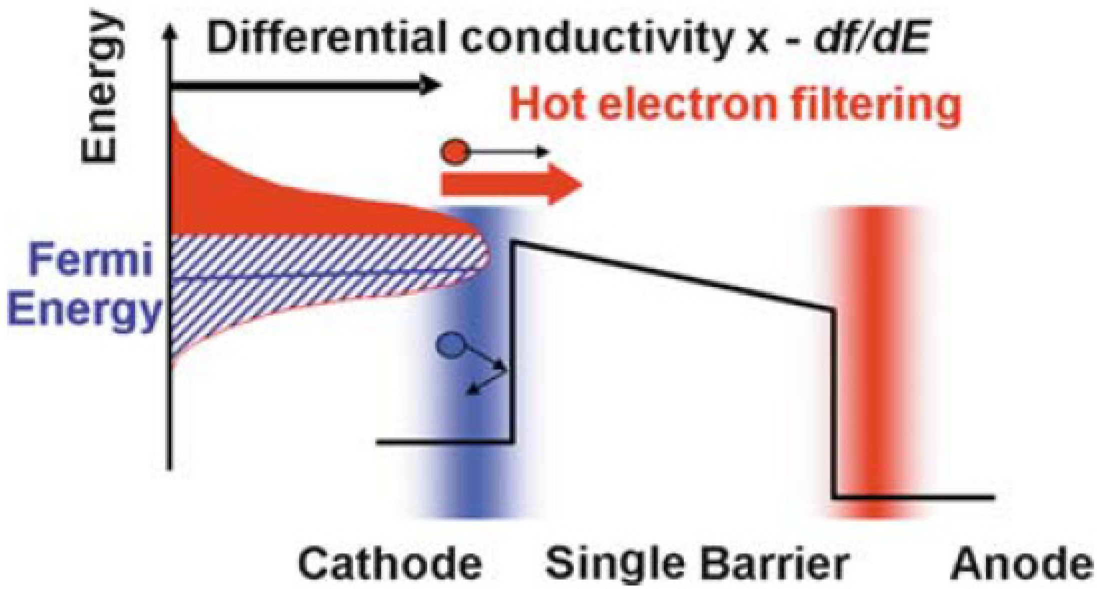
$$\eta = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + T_c/T_h}$$

- **Cooling** comparison: modern (mechanical) refrigerator efficiency equivalent to ZT ~ 3

- **Power generation** comparison: steam power plants are ~40% efficient



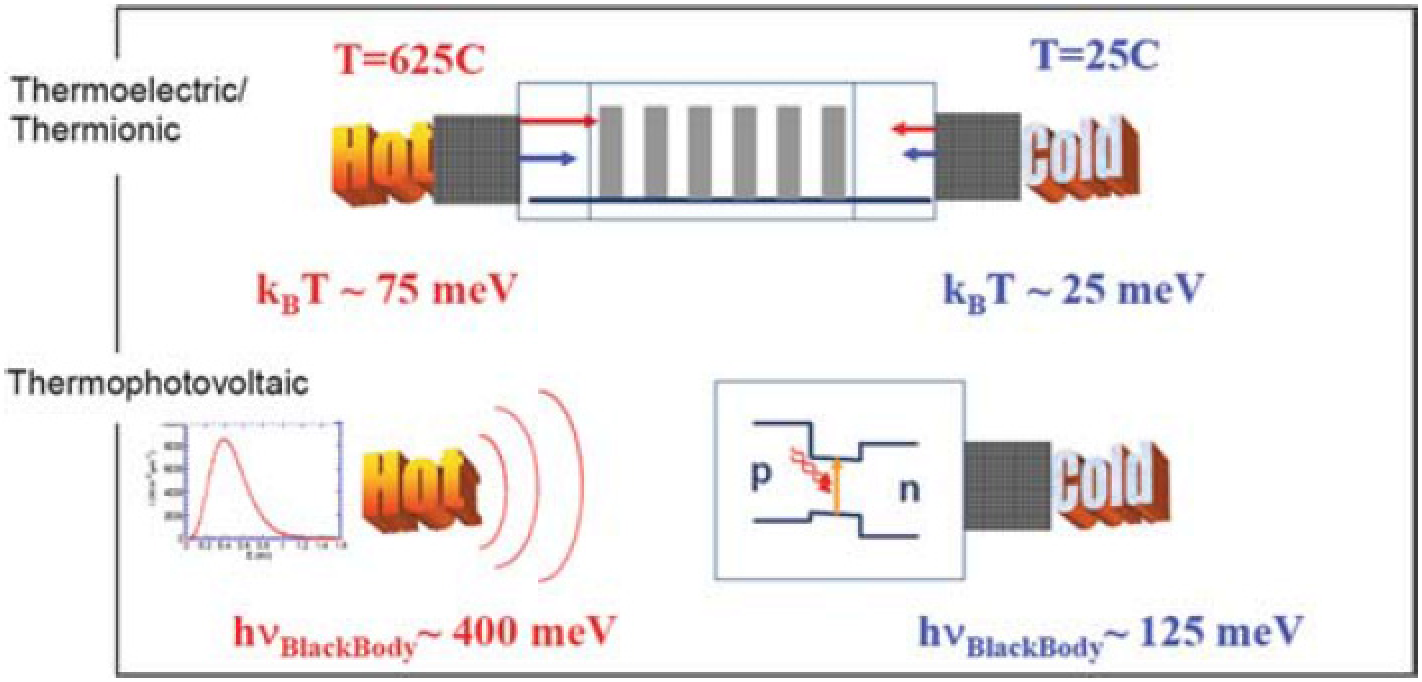
# Alternative: Thermionic (TI) Energy Conversion




- Design tunnel barrier that blocks (filters out) the cold electron distribution, to obtain maximum energy transmission
- Nanoscale vacuum gap is best electron (tunneling) conductor and worst thermal (phonon) conductor
- Challenges in controlling uniform tunnel gaps and efficiency only at higher temperatures

source: Shakouri (2010)

# Alternative: Thermophotovoltaics (TPV)




- Filter peak emission of thermal radiation from hot source
- Transmitted photons converted to electron-hole pairs in pn junction
  - TPV avoids some losses of conventional PV and heat backflow problem of TE
  - However, must avoid non-radiative recombination in pn junction

# Questions?

# Outline

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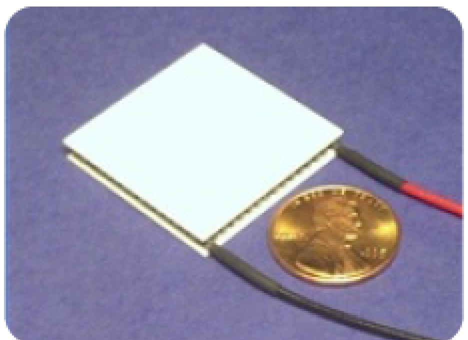
**2) Applications**

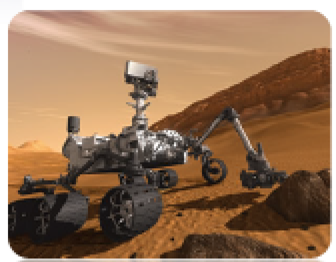
3) Final Remarks

# Thermoelectric Applications

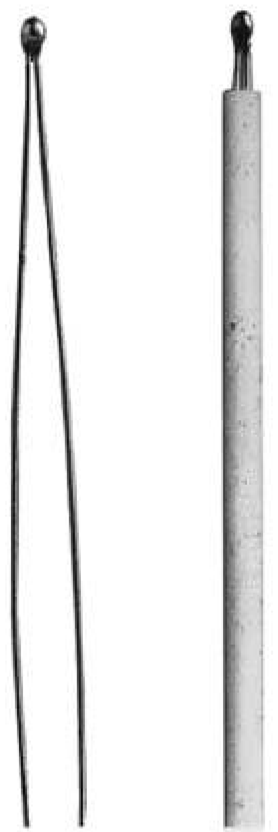


## Electric Cooling

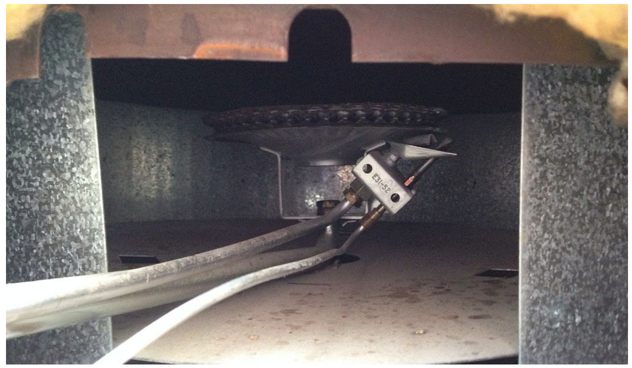
## Power Generation



# Thermocouples



inside water heater



inside meat thermometer



connected to multimeter

- Junction of two dissimilar materials, used to measure temperature (based on Seebeck's original experiment)

# Recap: Thermoelectric Modules

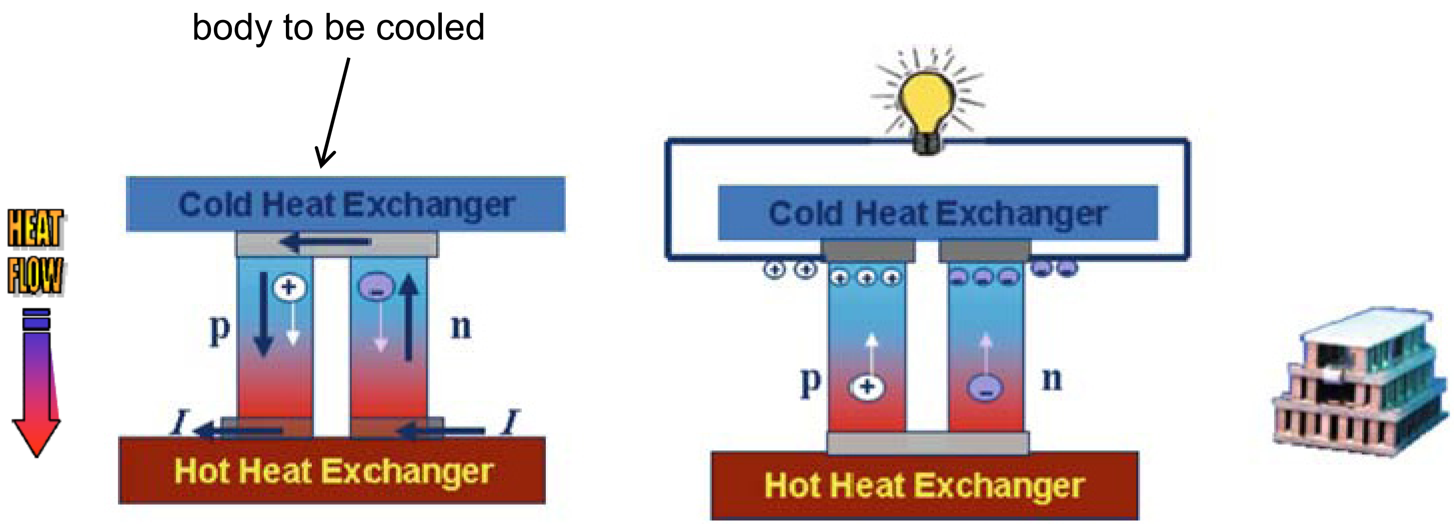



**Fig. 9.1** Thermoelectric devices. *Left*: Cooler based on Peltier effect. *Center*: Power generator based on Seebeck effect. *Right*: An actual module

- Use electrons and holes to carry heat and cool a body (e.g. cup holder)
  - Must have good electron and hole conductivity (high σ, S)
  - Must block heat "backflow" through (low k)
- Use temperature gradient (e.g. hot engine to ambient) to generate power
- No moving parts (=quiet and reliable), no freon (=clean)

# More Historical Perspective

- During and after world wars TE research grew, for both cooling and power generation for military and civilian uses
- Some advances could not be shared or were slow (US vs. USSR)
- 1950s: cooling from ambient to 0 $^{o}$C demonstrated (with $Bi_2Te_3$)
- Energy harvesting from oil lamp or camp fire to power radios

**Kerosene Radio** Made in Moscow for use in rural areas, this all-wave radio is reportedly powered by the kerosene lamp hanging above it. A group of thermocouples is heated internally to 570 degrees by the flame. Fins cool the outside to about 90 degrees. The temperature differential generates enough current to operate the low-drain receiver. Regular listeners may want fur-lined union suits, though: It works best in a room with open windows.

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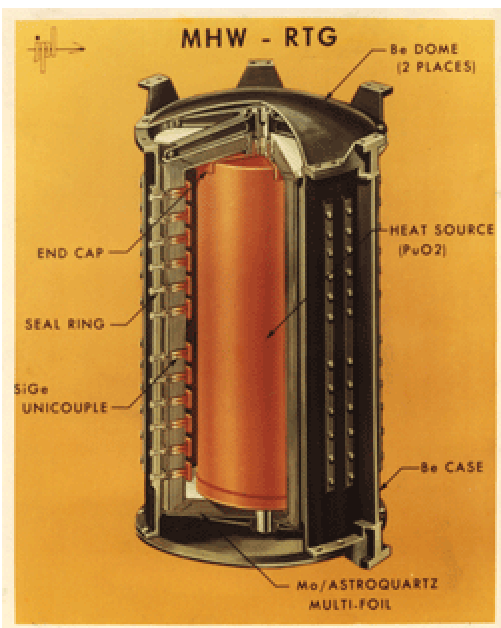
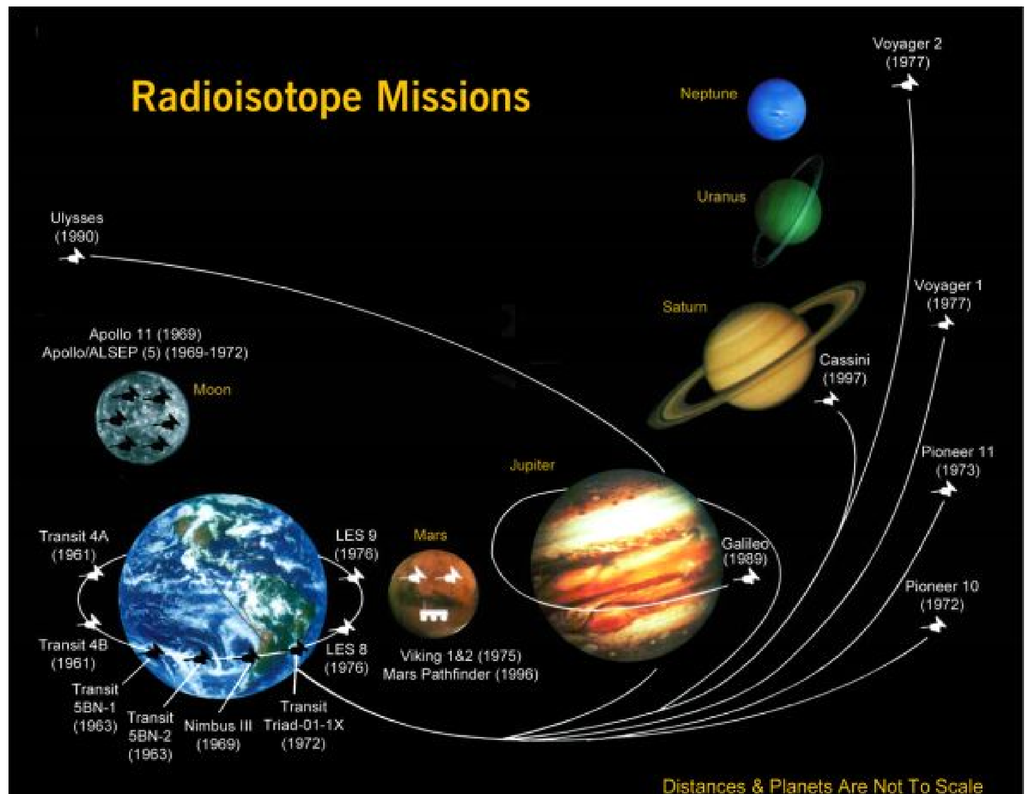
today: the BioLite camp stove phone charger ($130 at REI.com)

# Radioisotope Thermoelectric Generators (RTGs)

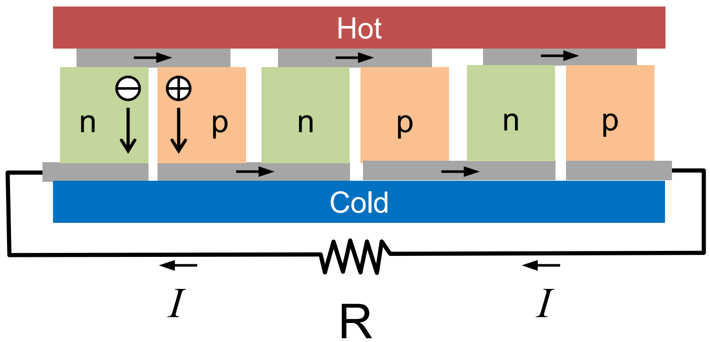
- For remote applications (e.g. lighthouses) and space exploration, electrical power provided by RTG
- RTG converts heat from decaying Pu-238 into electricity
  - Half-life of 90 years and 1 g sufficient for ~0.5 W power
- NASA used RTGs to power Apollo, Voyager, Viking, Curiosity…

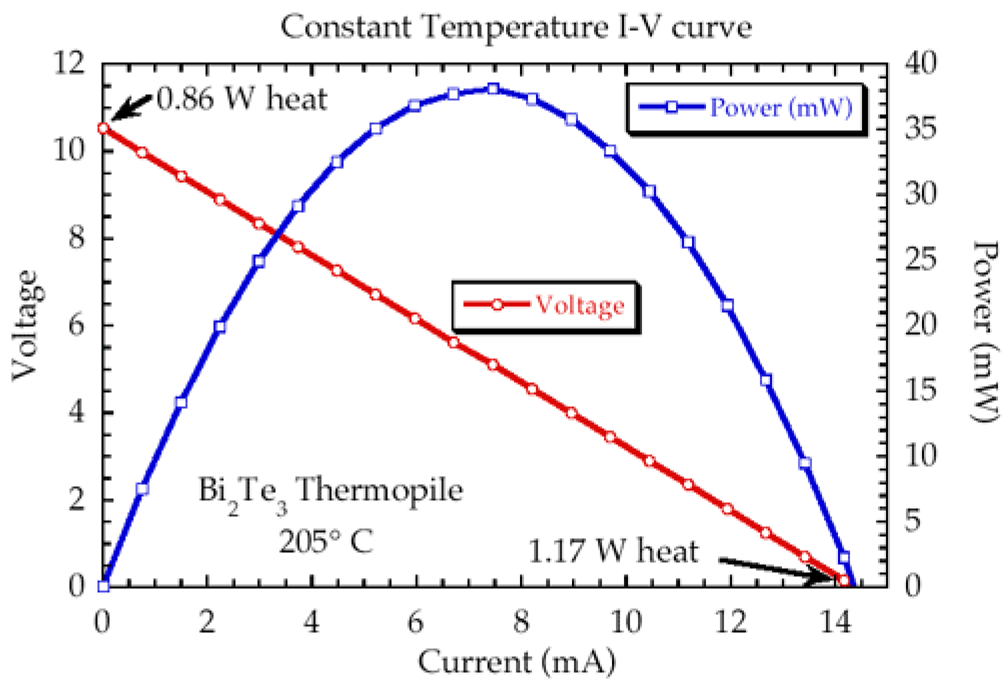



RTG for Voyager 1, 2



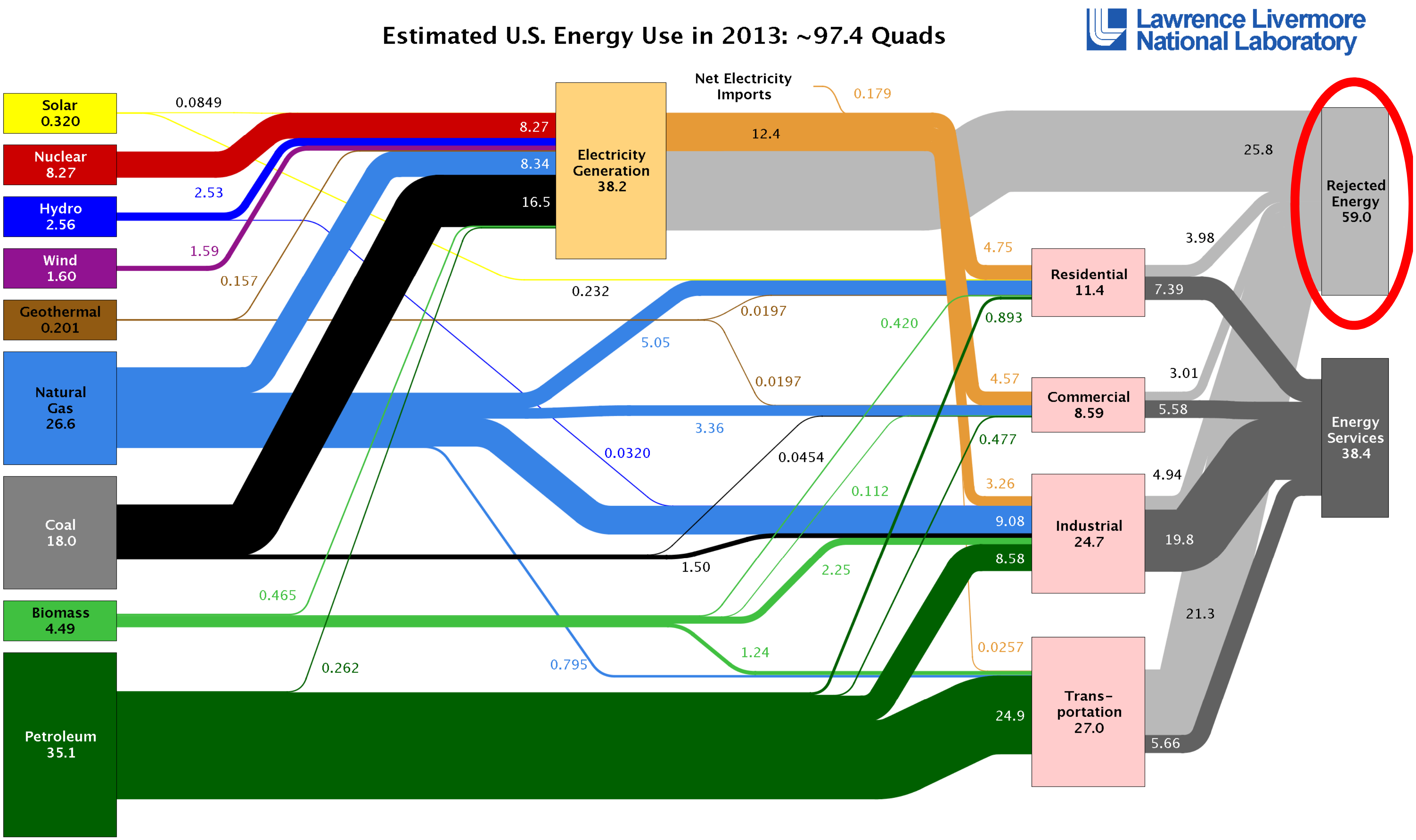
# Current-Voltage-Power Curve of a TEG



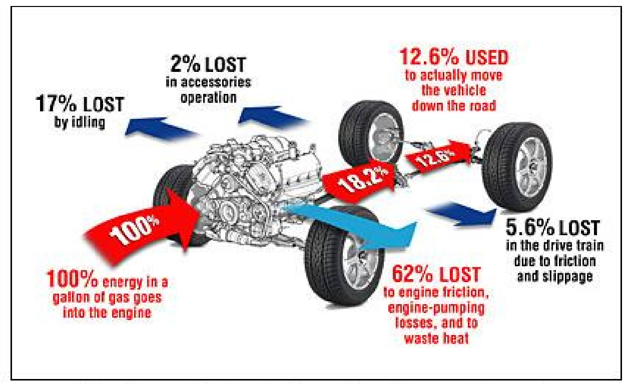

- In practice, the internal resistance of TEG and the external load resistance both matter
- Open circuit → max voltage, but no power produced
- High current → voltage is lost on the internal TEG resistance

# National Energy Perspective



# Energy Harvesting from Waste Heat

- Almost everything we do wastes heat
  - Power generation
  - Transportation (engine + friction)
  - Computing




- 15 TW (60%) wasted as heat in the world*
- Most is "low-grade" $T \leq 200\ ^{o}C$
- Recovering even a few percent would be HUGE, equivalent of several power plants (GW)

thermoelectrics could be a solution

*Dept. of Energy (2012). **By comparison, ALL data center power consumption world-wide is ~30 GW!**

# Recap: TEs for Refrigeration

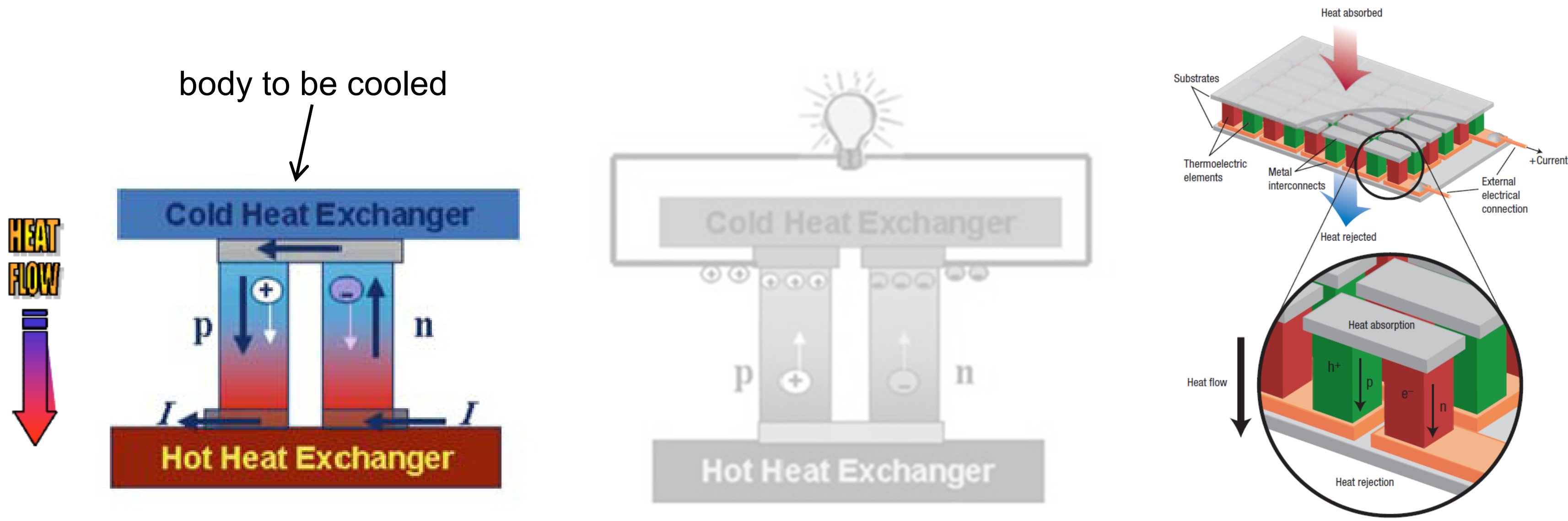



**Fig. 9.1** Thermoelectric devices. *Left*: Cooler based on Peltier effect. *Center*: Power generator based on Seebeck effect. *Right*: An actual module (sources: A. Shakouri, G. Snyder)

- Use junction ($\Delta S$) and current to electrically heat or cool
  - Peltier effect: $Q_{heat,cool} = \pm I \Delta S T$
- **Used in small refrigerators, cooled car seats, cup holders**
- No moving parts (=quiet and reliable), no freon (=clean)

# Recap: TEs for Power Generation

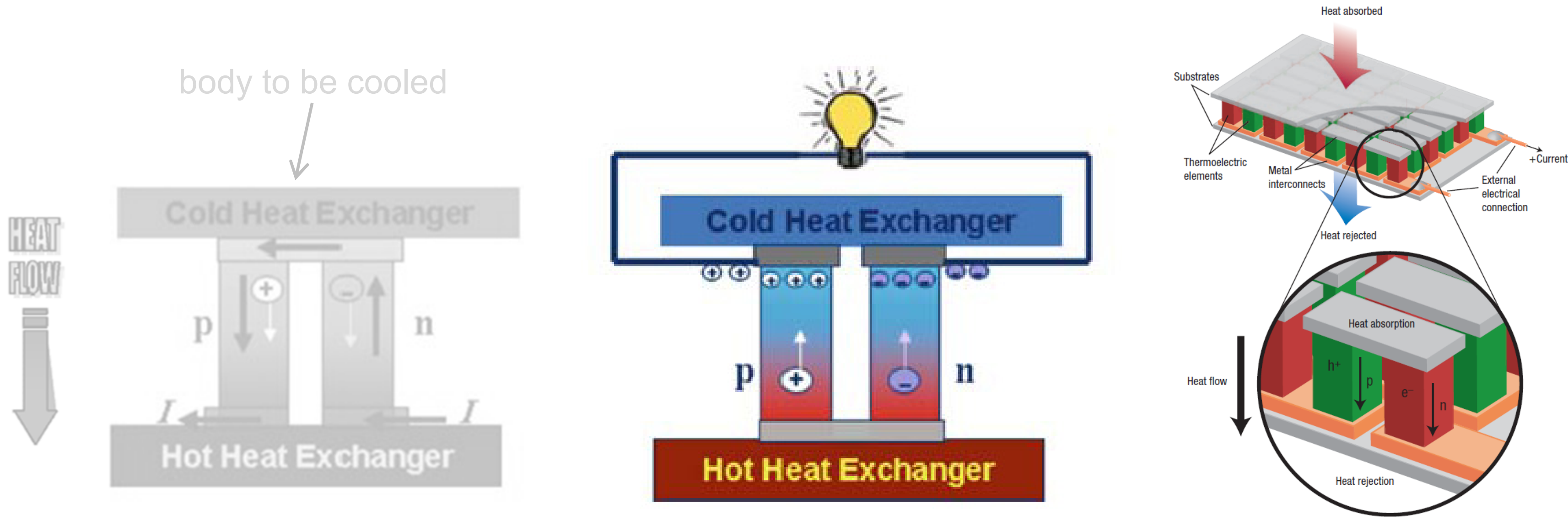
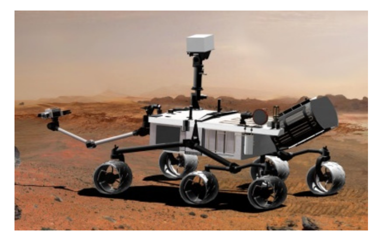


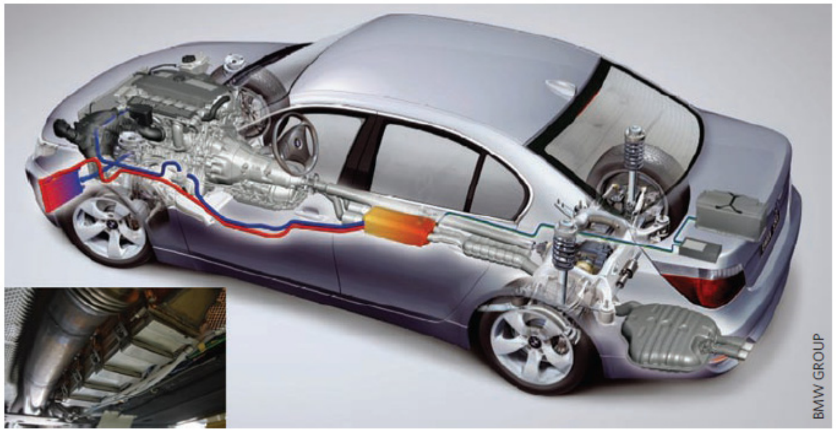

Fig. 9.1 Thermoelectric devices. *Left*: Cooler based on Peltier effect. *Center*: Power generator based on Seebeck effect. *Right*: An actual module (sources: A. Shakouri, G. Snyder)

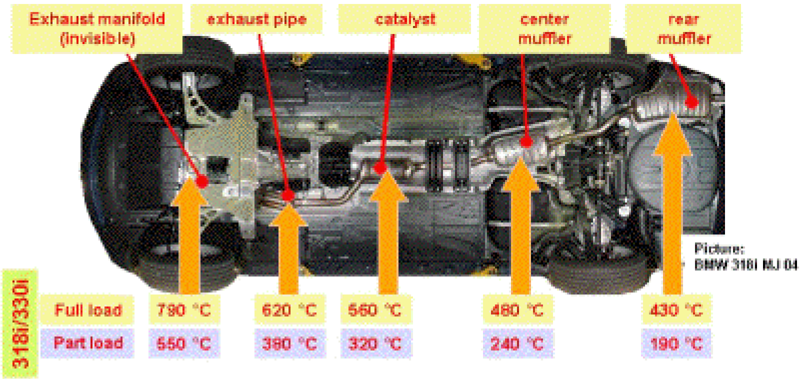


- Use temperature gradient ($\Delta T$) to generate power
  - Seebeck effect: $\Delta V \equiv S \Delta T$
- **Used in car engines & exhaust, Mars rover (~100 W)**
- No moving parts (=quiet and reliable), no freon (=clean)

# Ex: Automobile Waste Heat Recovery

- About 75% of energy from combustion lost as heat in exhaust or coolant
- Catalytic converters reach 300-500 C and TEGs can be used to harvest 100s of W
- Small fraction power recovery (consider 1 HP ≈ 750 W) but sufficient to power radio or AC and lessen alternator load



# An Important Perspective

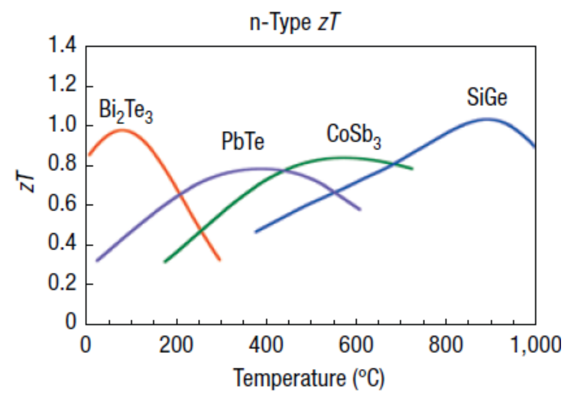
- "Thermoelectric energy conversion will never be as efficient as steam engines. That means thermoelectrics will remain limited to applications served poorly or not at all by existing technology" (Vining, 2009*)

- However:
  - TEs could play a big role in waste heat recovery
  - Cooling in small size applications (e.g. lasers, seats, cup holders)
  - What matters is not just efficiency (ZT), but cost per Watt
    - *Many groups are looking at polymer TEs even though efficiency is lower than traditional semiconductors, paralleling work in solar cell community*
  - Power generation in communities without power plants and electric grid
    - *TE modules in cooking stoves and solar thermal systems*

*Vining, "An Inconvenient Truth About TEs" (2009)

# New Materials for Thermal Energy Harvesting

- Traditional thermoelectrics: Bi, Te, Pb → rare, expensive, toxic, brittle




| Material | Cost ($/kg) |
|---|---|
| $Bi_2Te_3$ (bulk) | 110 |
| $Bi_{0.52}Sb_{1.48}Te_3$ | 125 |
| PEDOT:PSS (polymer) | 0.34 |

G. Snyder, *Nature Mat.* (2008); S. Yee *et al.* (2013)

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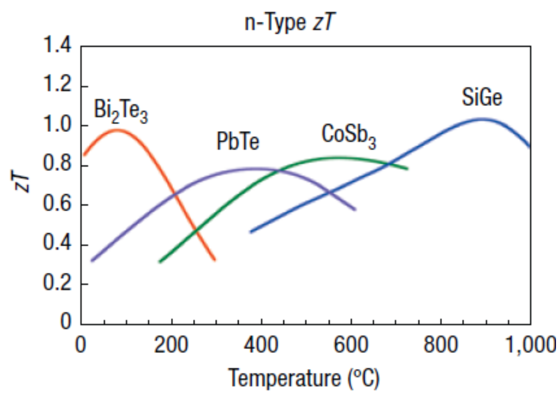
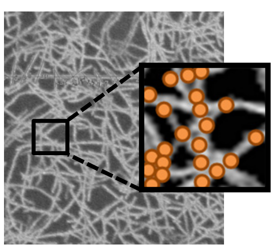
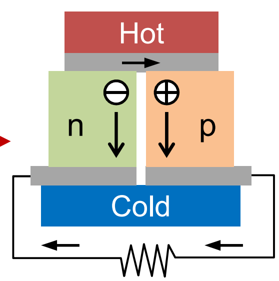
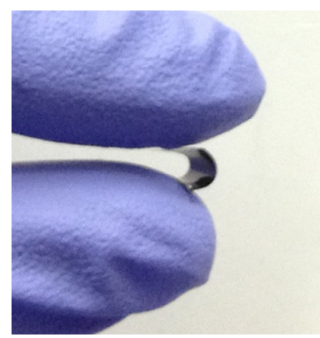



| Material | Cost ($/kg) |
|---|---|
| $Bi_2Te_3$ (bulk) | 110 |
| $Bi_{0.52}Sb_{1.48}Te_3$ | 125 |
| PEDOT:PSS (polymer) | 0.34 |

- Start with **low-cost polymers*** that already have low *k*, high *σ*
- Use nanostructuring (nanotubes, nanowires) to increase *S*





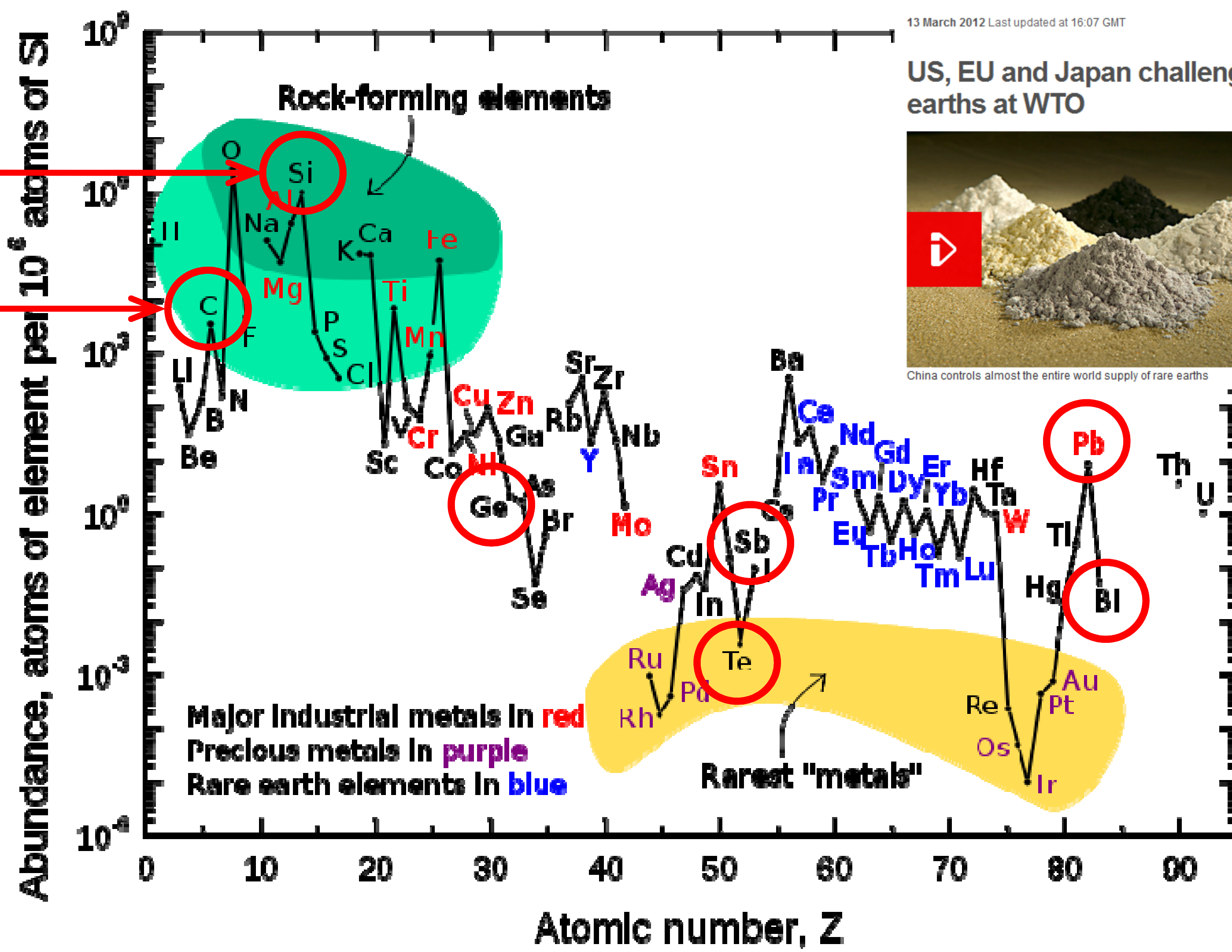



**Bonus:**
- mechanically flexible
- solution processable

G. Snyder, *Nature Mat.* (2008); S. Yee *et al.* (2013)

*Berkeley and LBNL (J. Urban and R. Segalman)

# Abundance of Materials





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13 March 2012 Last updated at 16:07 GMT

455 Share

US, EU and Japan challenge China on rare earths at WTO

China controls almost the entire world supply of rare earths

source: http://pubs.usgs.gov/fs/2002/fs087-02

# Energy Harvesting From the Human Body

**Power Consumption**

desktop PC ~ 100 W
notebook PC ~ 10 W
low-power sensor, µchip ~ µW – mW

**human body output at rest ~ 100 W**

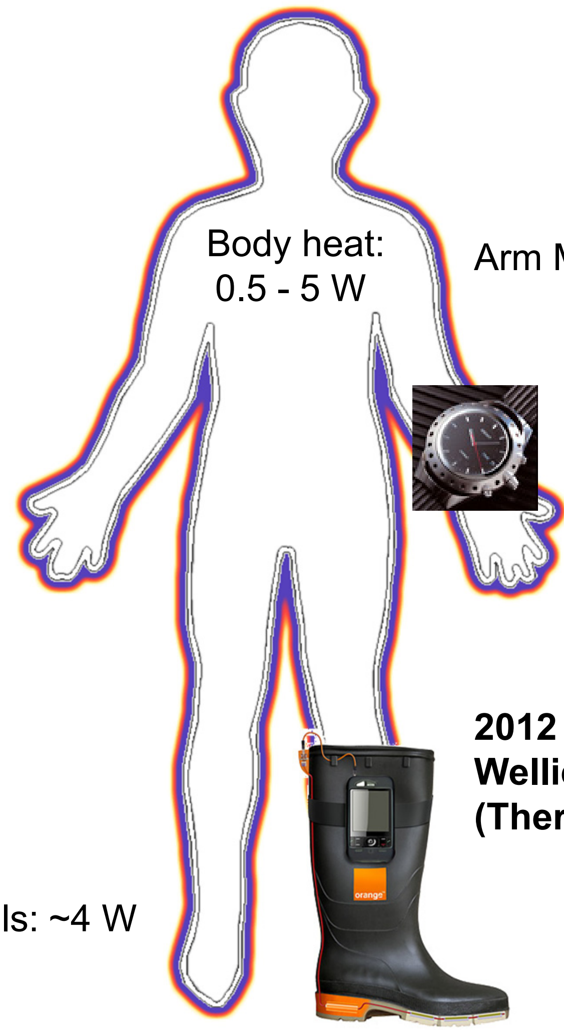
**What's The Upper Limit (Carnot)?**

$$\eta_{carnot} = \frac{T_{body} - T_{ambient}}{T_{body}} = \frac{310 - 293\ K}{310\ K} \approx 5\%$$

$$\eta_{carnot} \times \eta_{TE} \approx 0.5\%$$

must maximize $ZT = \dfrac{S^2 \sigma T}{k_{th}}$

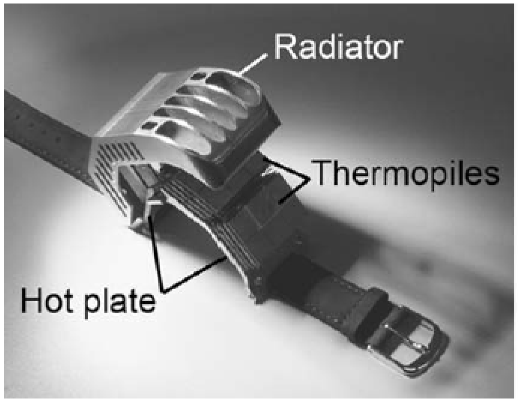
**Usable Power From The Body:**

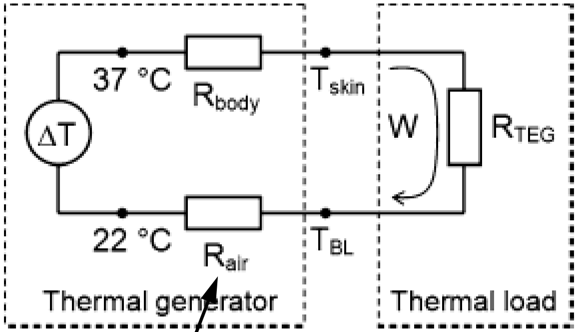



T. Starner, *IBM Systems Journal*, **35** (1996)

# Optimizing Human Energy Harvesting

- Body heat powered watches, boots already demonstrated
- Maximum power harvested is ~180 μW/cm$^2$ between skin (34 $^o$C) and air (22 $^o$C)
- However, full $\Delta T$ = 12 $^o$C is not dropped across TEG
- Key is maximizing internal TEG thermal resistance ($R_{TEG}$) and minimizing TEG-air thermal resistance ($R_{air}$)
- Most also minimize TEG contact resistance (flex-TEG)




parasitics!

source: V. Leonov (2009)

# Outline

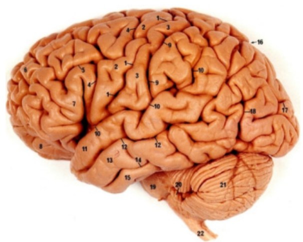
1) Fundamentals

2) Applications

**3) Final Remarks**

# What Motivates Our Research Group

(IBM Watson, *Jeopardy!* champion)



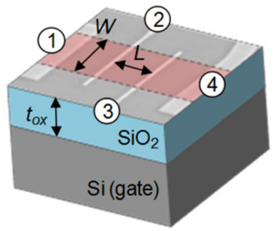
20 Watts

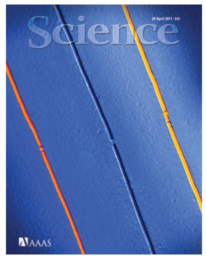

200 kiloWatts

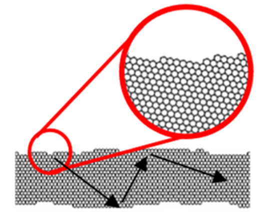
10,000x

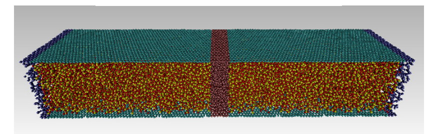
(conventional Moore's Law size scaling can get us ~10x)

# Our Work: Two Sides of the Same Coin



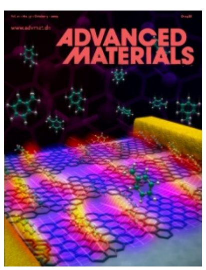



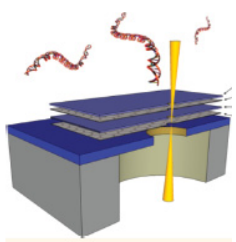
**Lower power at its source**

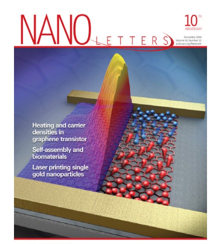
(devices, sensors, circuits)

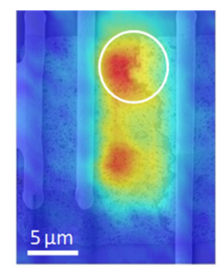
**Harvest and manage heat**

(energy, thermoelectrics)






**fundamental understanding**

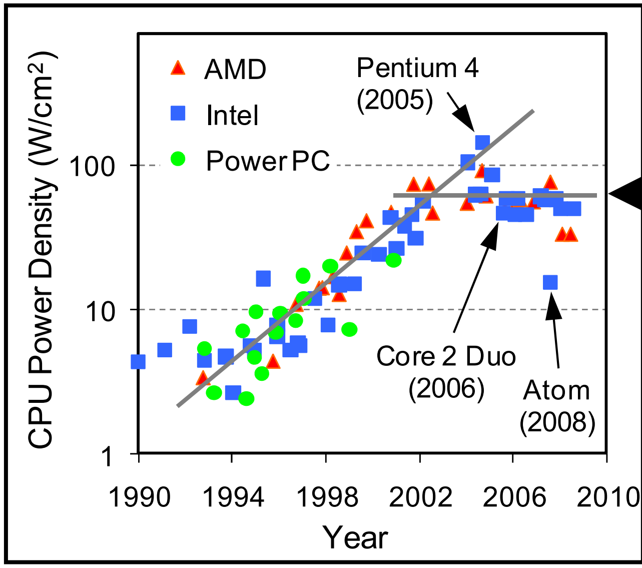
**practical applications**

# Pop Lab: Energy and Electronics

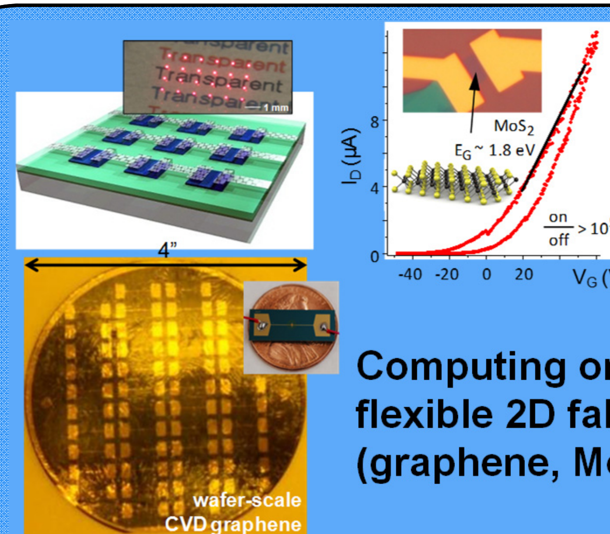
http://poplab.stanford.edu

review: E. Pop, *Nano Research* 3, 147 (2010)

**new course: EE 323 "Energy in Electronics" in Autumn 2014**



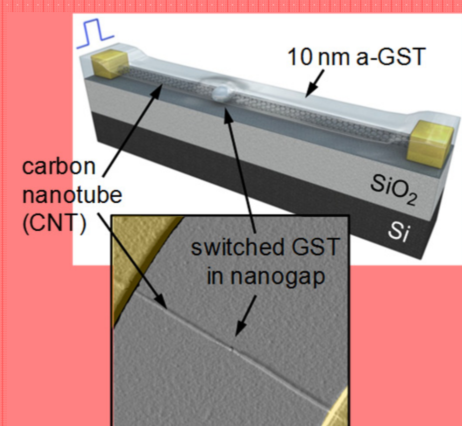

**Electronics, limited by power & heat since 2005!**




**Computing on flexible 2D fabrics (graphene, $MoS_2$)**

**Energy-efficient data storage:**

**100x lower power in phase-change memory (PCM)**

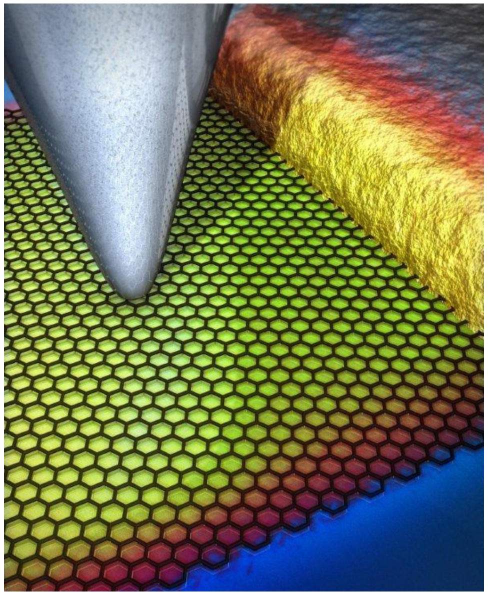



Xiong et al, *Science* (2011)

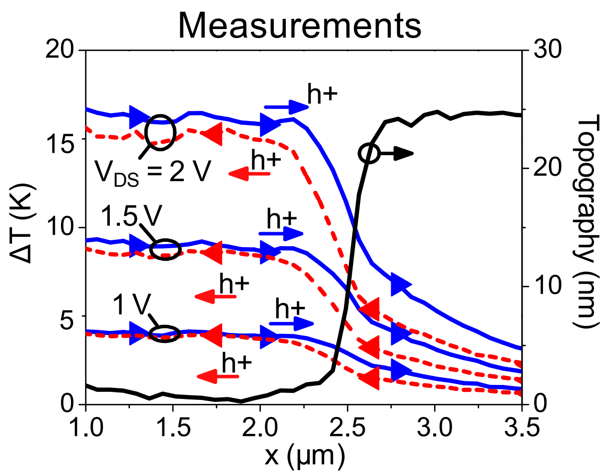
**Energy harvesting: up to ~1 W from body heat using flexible thermoelectrics (TE)**

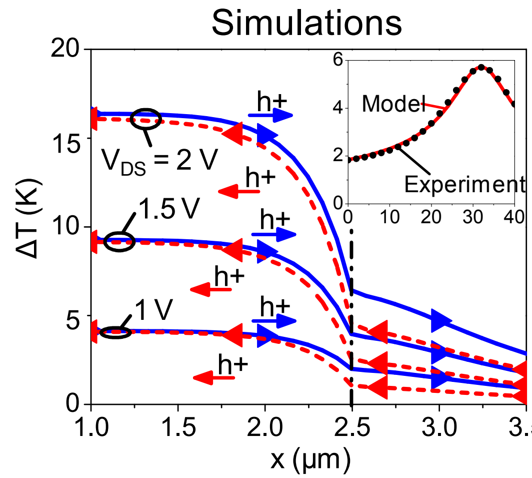
# Thermoelectric Effects at Nanoscale Contacts

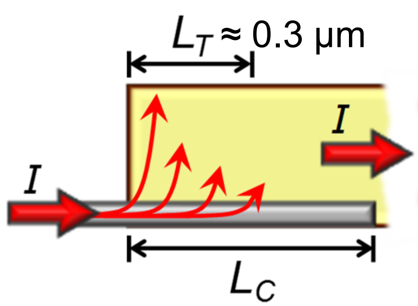
K. Grosse, M.-H. Bae, F. Lian, E. Pop, W. King, *Nature Nano* 6, 287 (2011)



scanning Joule expansion microscopy (SJEM)



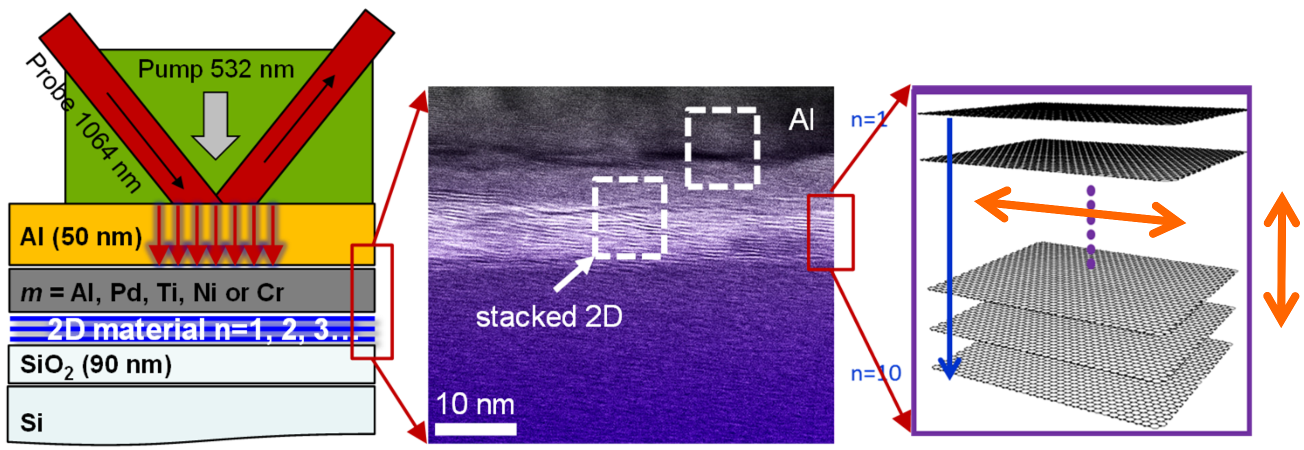




- AFM-based thermometry (SJEM)
- Contact temperature due to:
  - Current crowding (CC) } 2/3
  - **Thermoelectric effect (TE)** } **1/3**
- Some 2D materials have large thermopower S
  - Engineer cooling at device contacts?
  - Design built-in TE coolers?

# Looking Ahead: Unusual 2D Materials

- **Large in-plane** thermal conductivity of graphene (>1000 W/m/K)
- **Ultra-low cross-plane** thermal conductivity of layered $WSe_2$ (<0.1 W/m/K)
  - Lower than plastics and ***comparable to air****
- Huge thermal anisotropy in all layered 2D materials (>10-100x)**



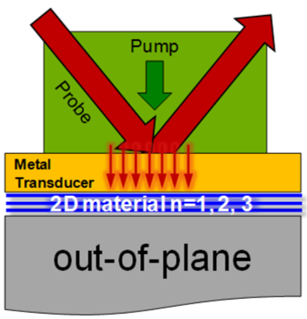

- **Large thermopower** in some 2D materials (~0.5 mV/K)
- Favorable properties for thermoelectrics

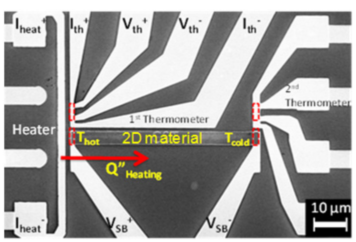
*C. Chiritescu et al., *Science* (2007)
**E. Pop, V. Varshney, A. Roy, *MRS Bulletin* (2012)
**D. Estrada, Z. Li, F. Lian, […], E. Pop, *in preparation* (2014)

# Looking Ahead: Future Opportunities

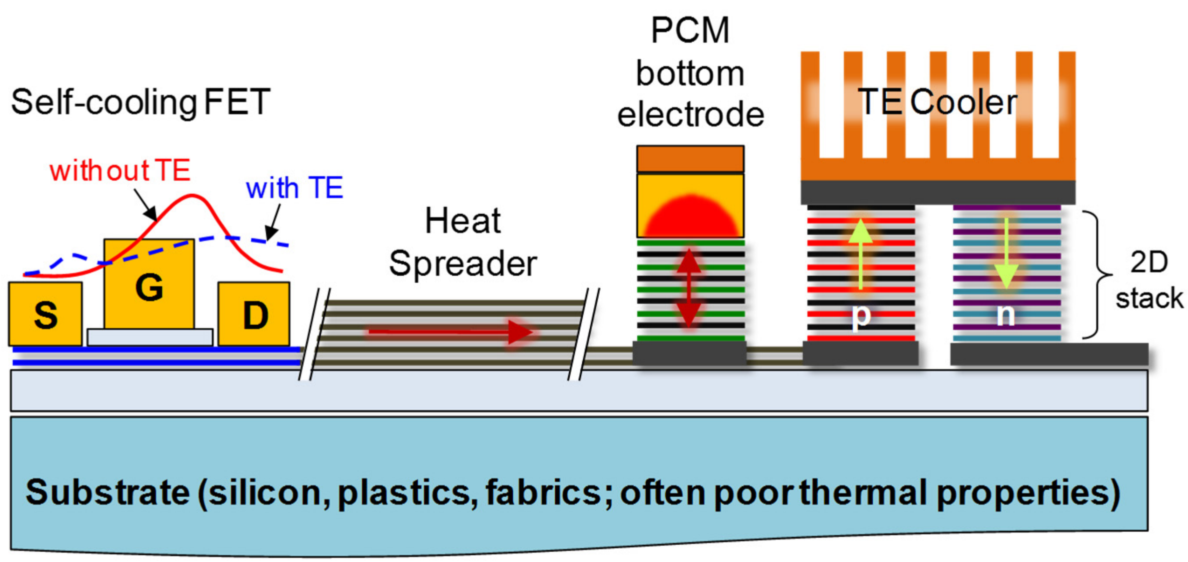
## Could we:

- Exploit **anisotropy** for low-power electronics? (e.g. phase-change memory)
- Separate thermal and electrical flow? (thermal transistor)
- Design **electronics with built-in thermoelectric cooling**?
- Achieve transparent heat spreaders and flexible thermoelectrics?

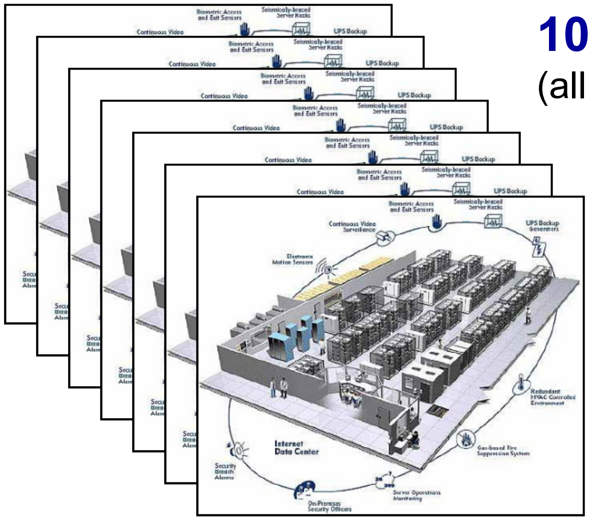



in-plane

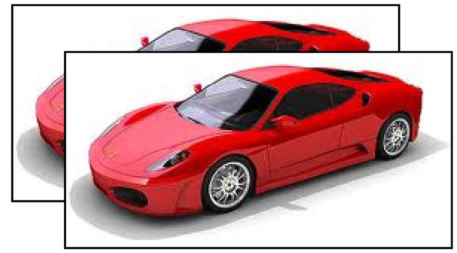


# What Is 10,000x Electrical Power Reduction?



**10 GW**
(all data centers in US)

÷ 10,000



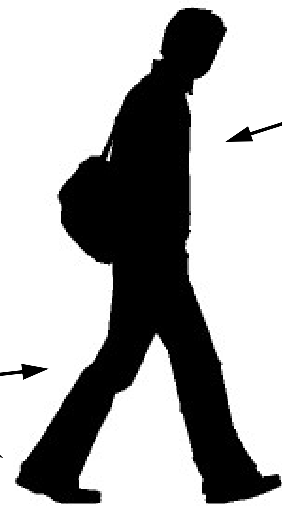
**1 MW**
(2 Ferrari F430)
(solar power from 1 parking lot)

**50 mW**
(average)

÷ 10,000

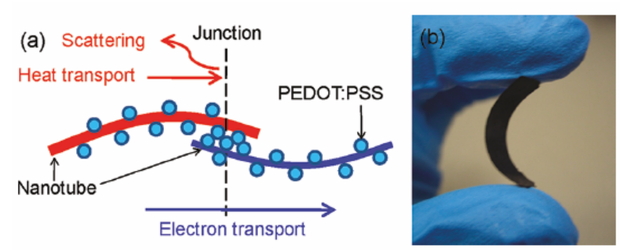
**5 μW**
(powered by body heat)

# Low Power Devices + Energy Harvesting



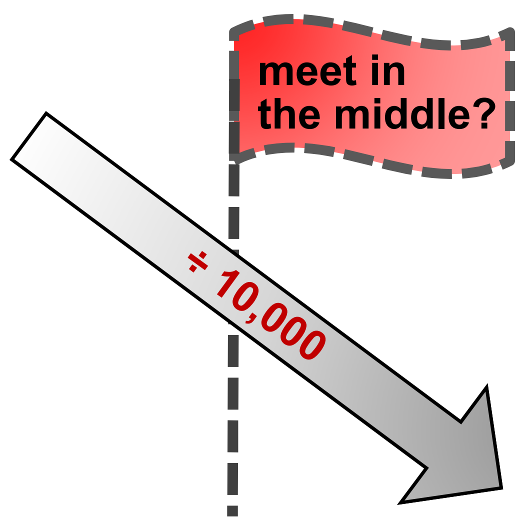
**up to ~1 W body heat**
(thermoelectrics)

up to ~4 W walking
(piezoelectricity)




flexible thermoelectrics
Yu et al, *ACS Nano* (2011); Lian et al (in preparation)

**50 mW**
(average)

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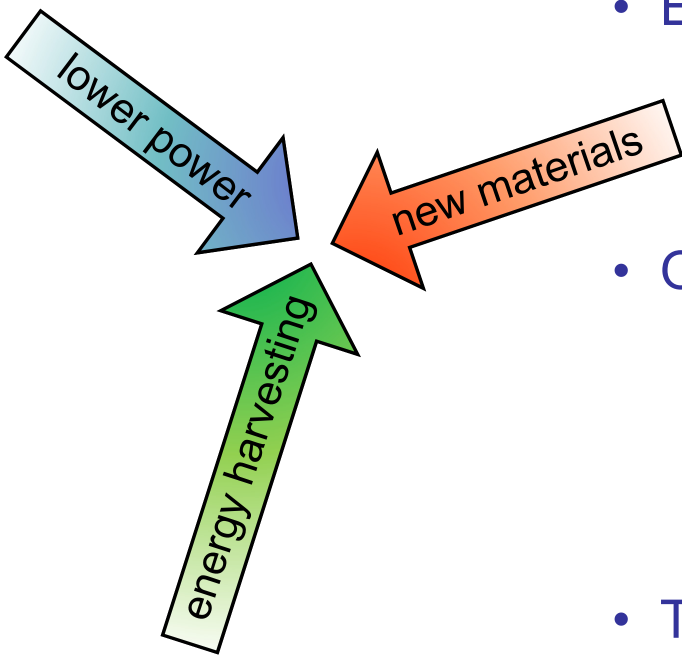
# Summary




- Moore's Law ~10x → slowing down
- Energy scaling & harvesting ~$10^4$x → exciting

- Opportunity for convergence of:
  – Low power electronics
  – **Energy harvesting**
  – Novel nanomaterials
- Towards fundamental limits of energy use (up to 10,000x improvements may be possible)

MUCH room for optimization of energy dissipation, use, and harvesting from the "atomic" level

# Key References


- http://www.thermoelectrics.caltech.edu (web tutorial)
- http://core.kmi.open.ac.uk/download/pdf/11784960.pdf (historical)
- http://www.crcnetbase.com/isbn/978-0-8493-0146-9 (CRC Handbook of TEs)
- http://dx.doi.org/10.1002/adma.201000839 (nanostructured TEs)
- http://dx.doi.org/10.1146/annurev-matsci-062910-100445 (recent developments)
- http://dx.doi.org/10.1038/nmat2361 (inconvenient truth)
- http://dx.doi.org/10.1039/C3EE41504J ($/W metrics)
- http://dx.doi.org/10.1016/j.rser.2013.12.030 (material and manufacturing costs)
- http://dx.doi.org/10.1063/1.4803172 (nanoscale Peltier in data storage)
- http://dx.doi.org/10.1007/s11664-008-0638-6 (wearable TEGs)