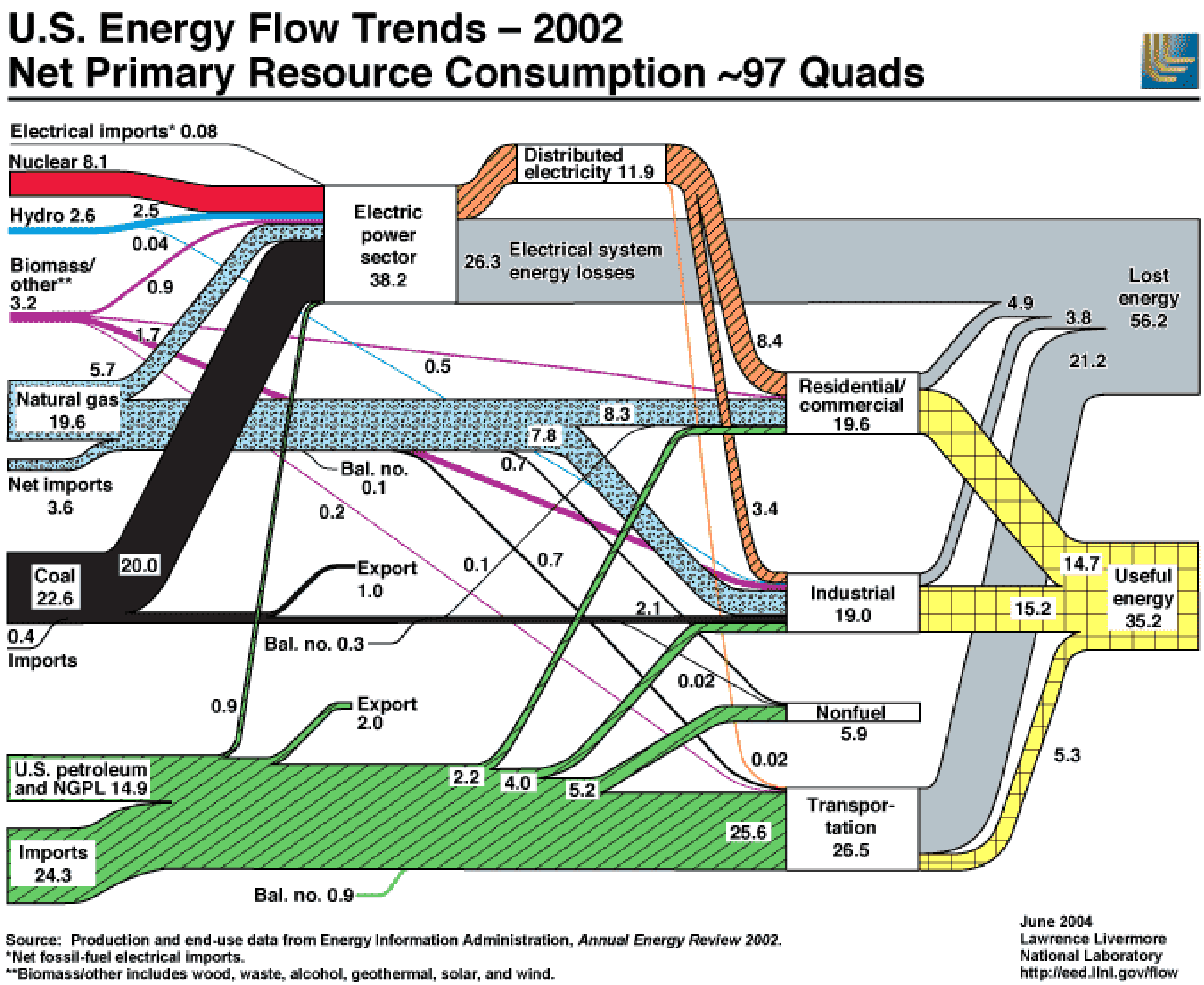
Importance of Heat



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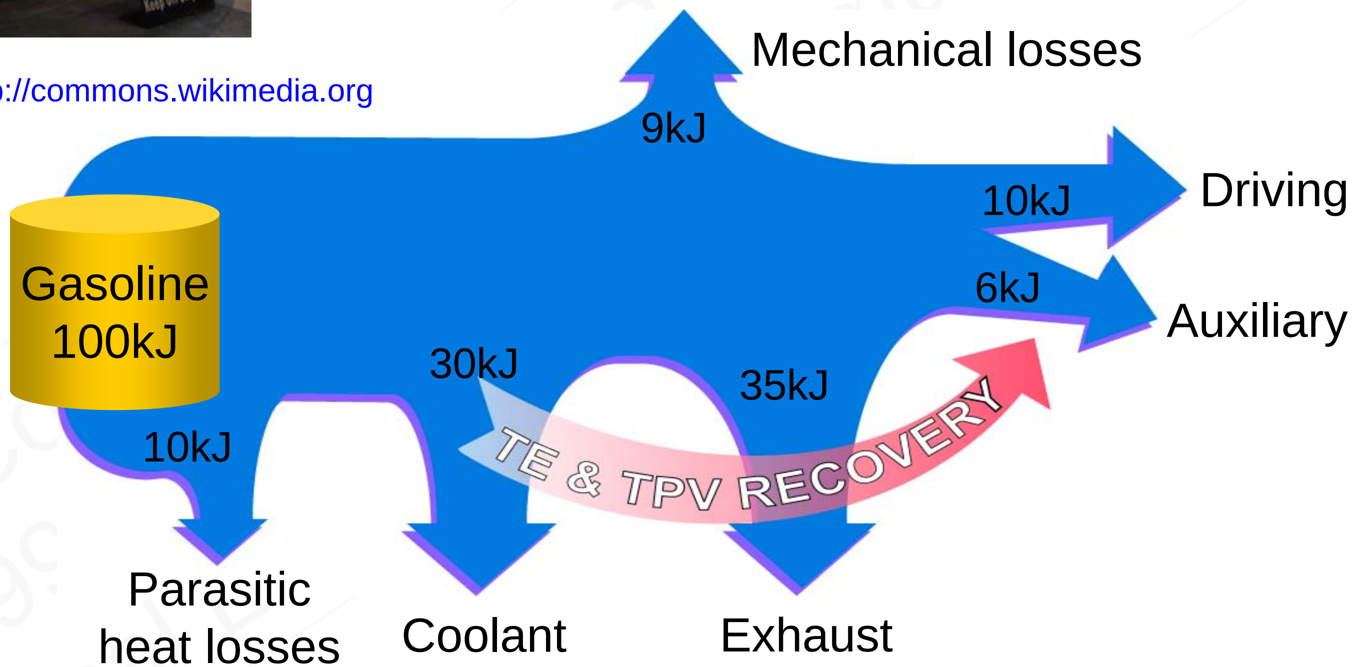
Vehicle Systems

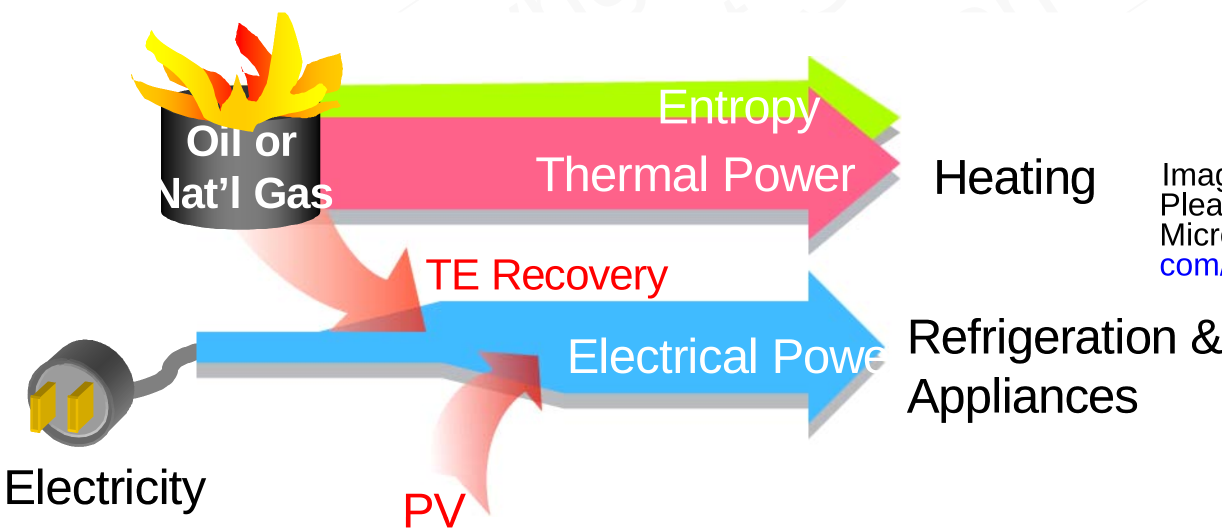


- **In US, transportation uses ~26% of total energy.**

Co-Generation in Residential Buildings

Photo by bunchofpants on Flickr.

In US, residential and commercial buildings consume ~35% energy supply



Industrial Waste Heat

Photos by arbyreed and toennesen on Flickr.

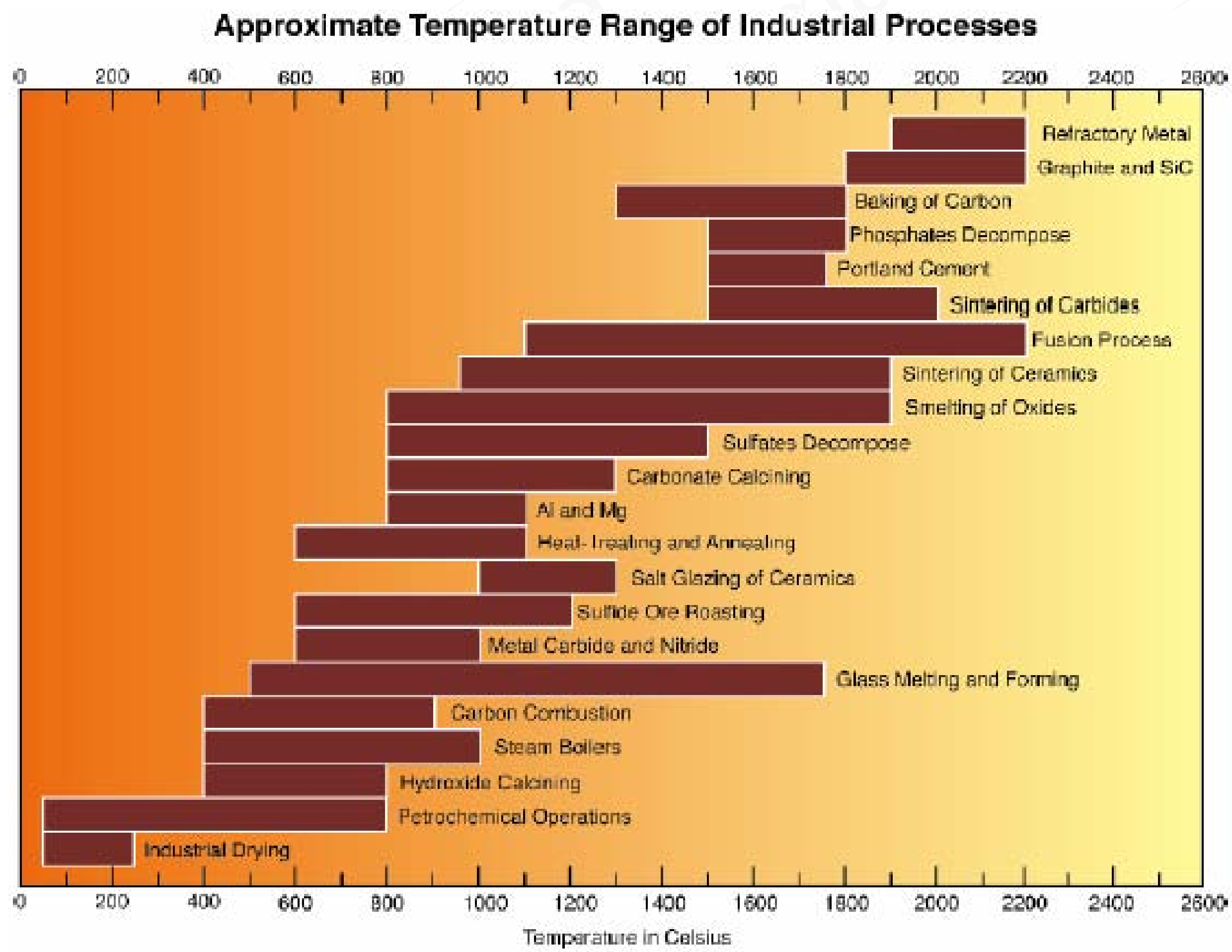
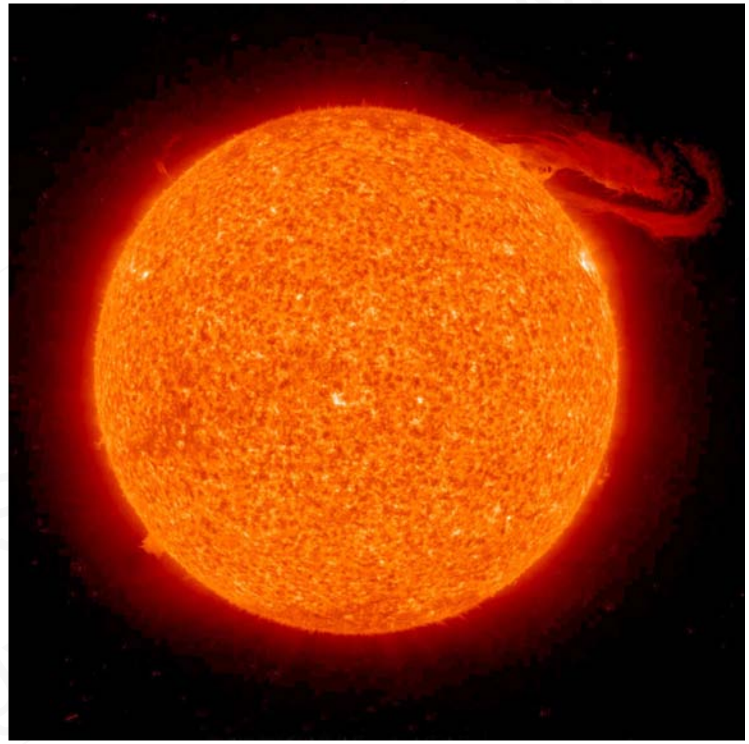


Fig. ES.1 in Hemrick, James G., et al. "Refractories for Industrial Processing: Opportunities for Improved Energy Efficiency." DOE-EERE Industrial Technologies Program, January 2005.

Renewable Heat Sources



Photos by Jon Sullivan at http://pdphoto.org/ and NASA.

Solar Thermal

Photos of solar hot water tubes removed due to copyright restrictions. Please see, for example,
http://image.made-in-china.com/2f0j00KeoavBGJycbN/Unpressurized-Solar-Water-Heater-VERIOUS-.jpg
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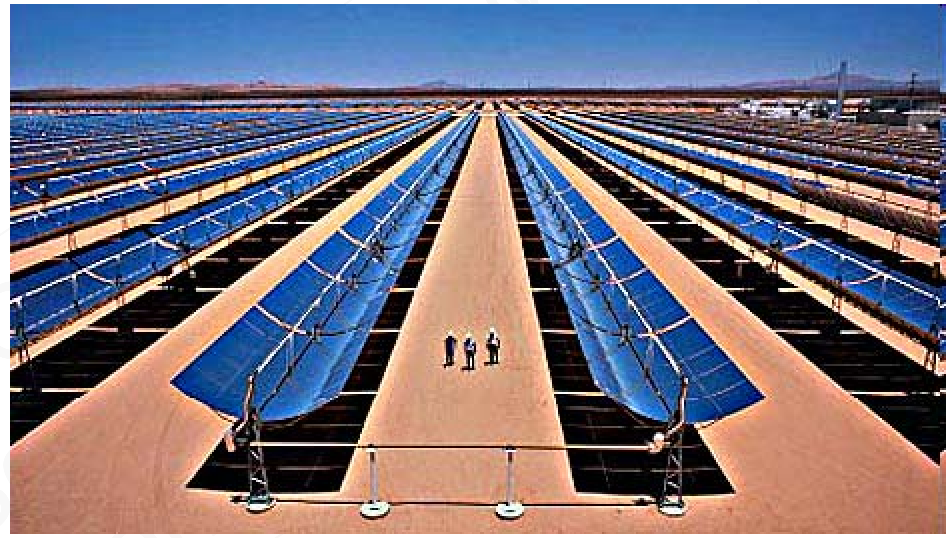

http://www.treehugger.com/Solar-Thermal-Plant-photo.jpg

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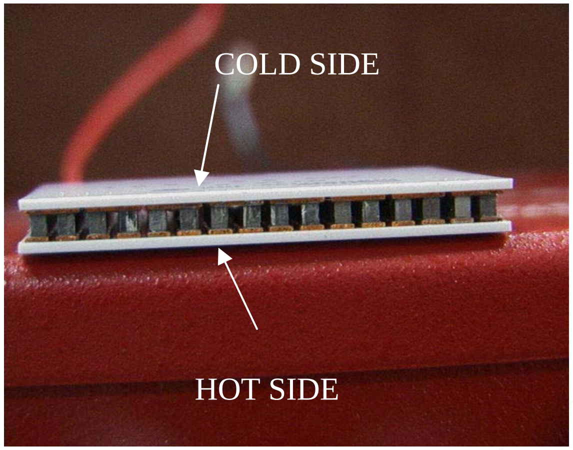
Direct Energy Conversion



Thermoelectrics

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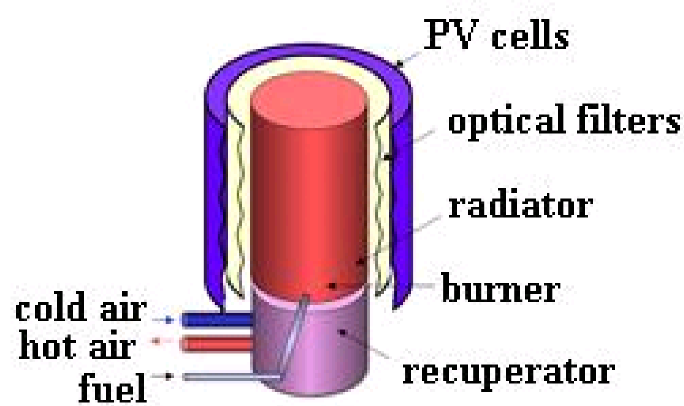
Please see http://web.archive.org/web/20071011185223/www.eneco.com/images/science-new.jpg

Photovoltaics

http://www.solareis.anl.gov/images/photos/Nrel_flatPV15539.jpg

Image by Nadine Y. Barclay, USAF.

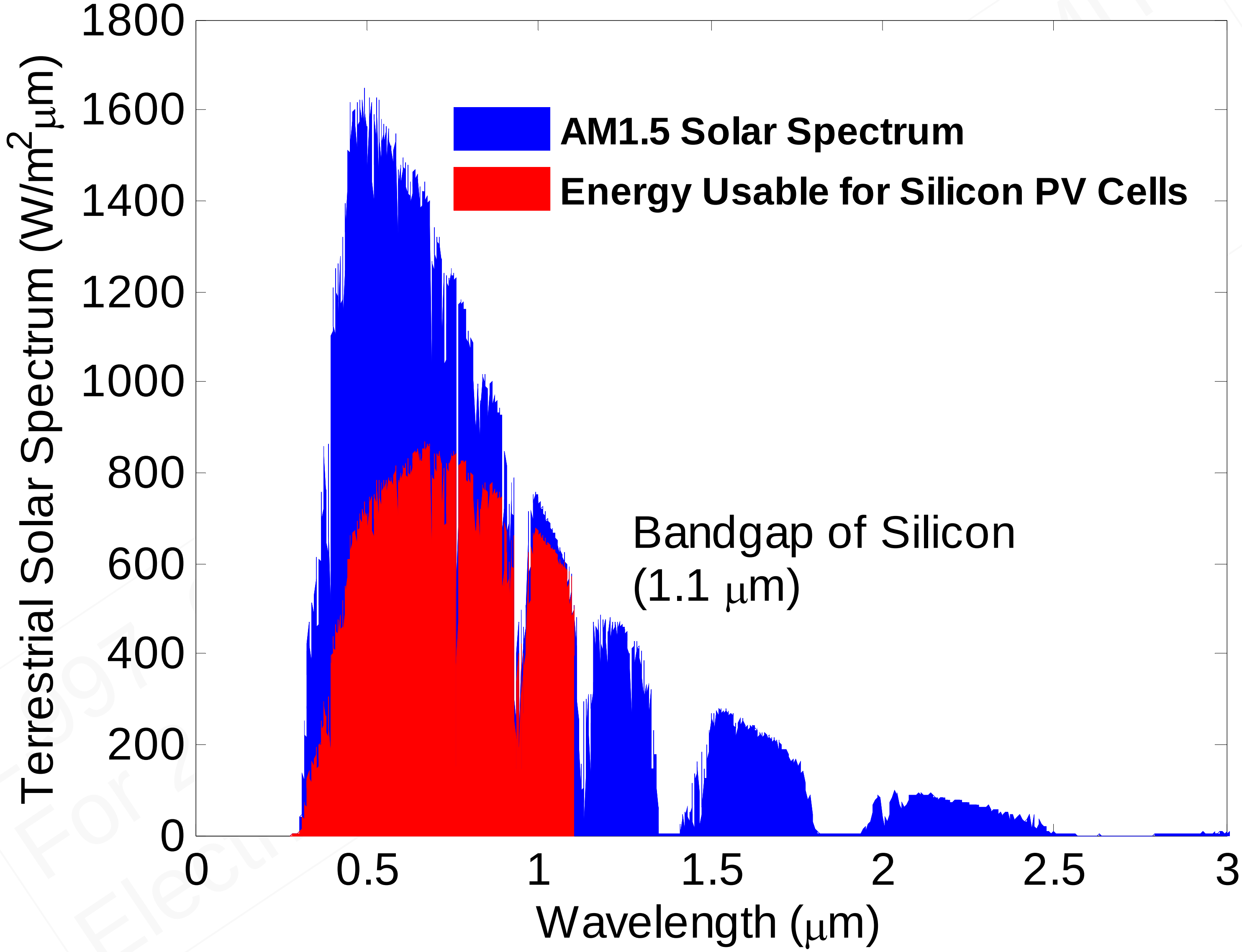


Thermophotovoltaics

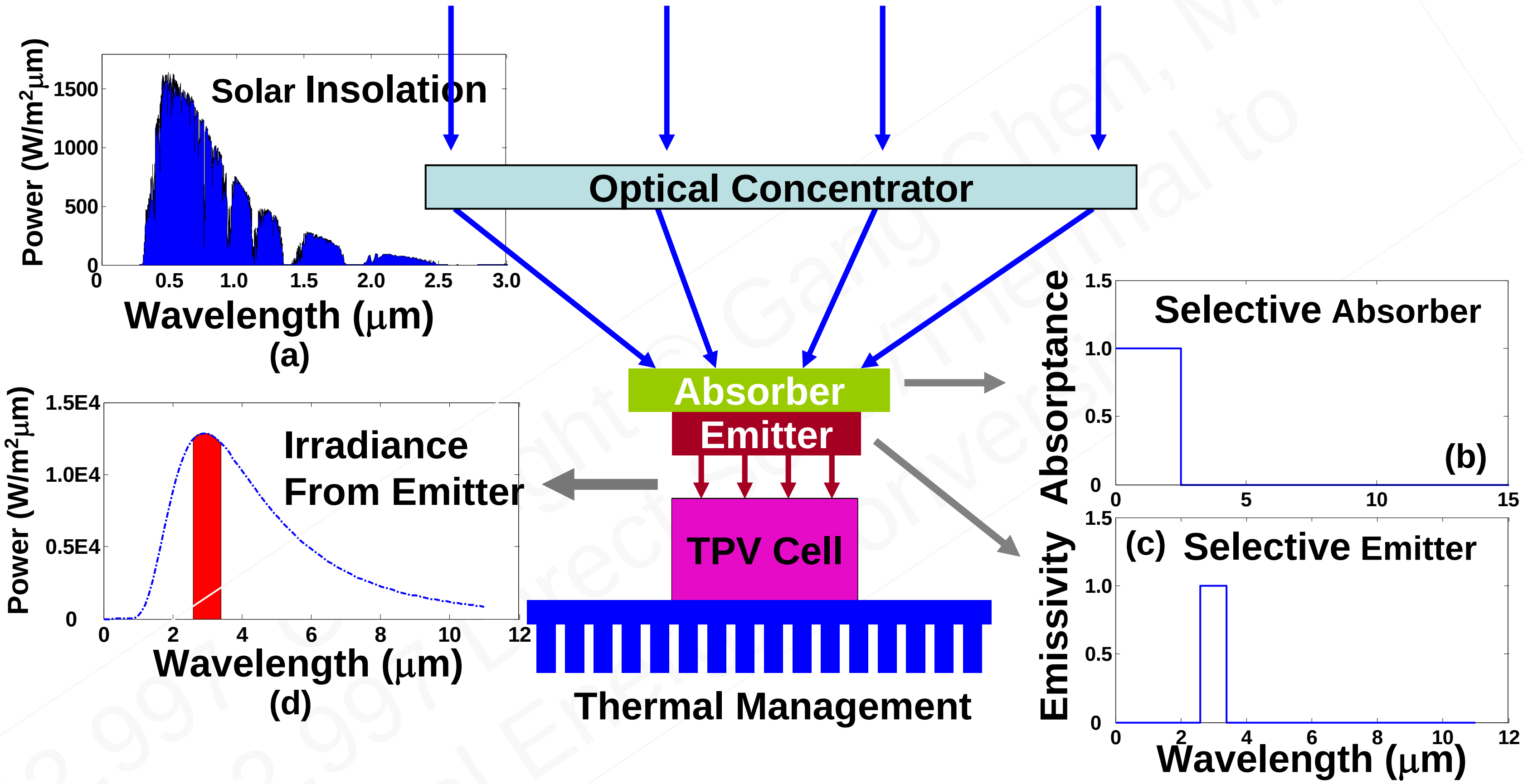
http://www.keelynet.com/tpvcell.jpg

Courtesy of John Kassakian. Used with permission.

Solar Spectrum

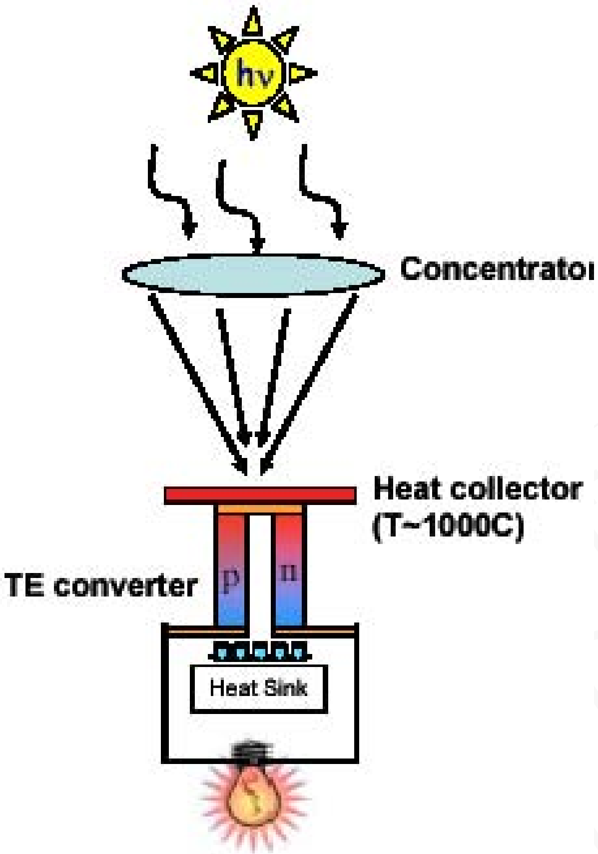


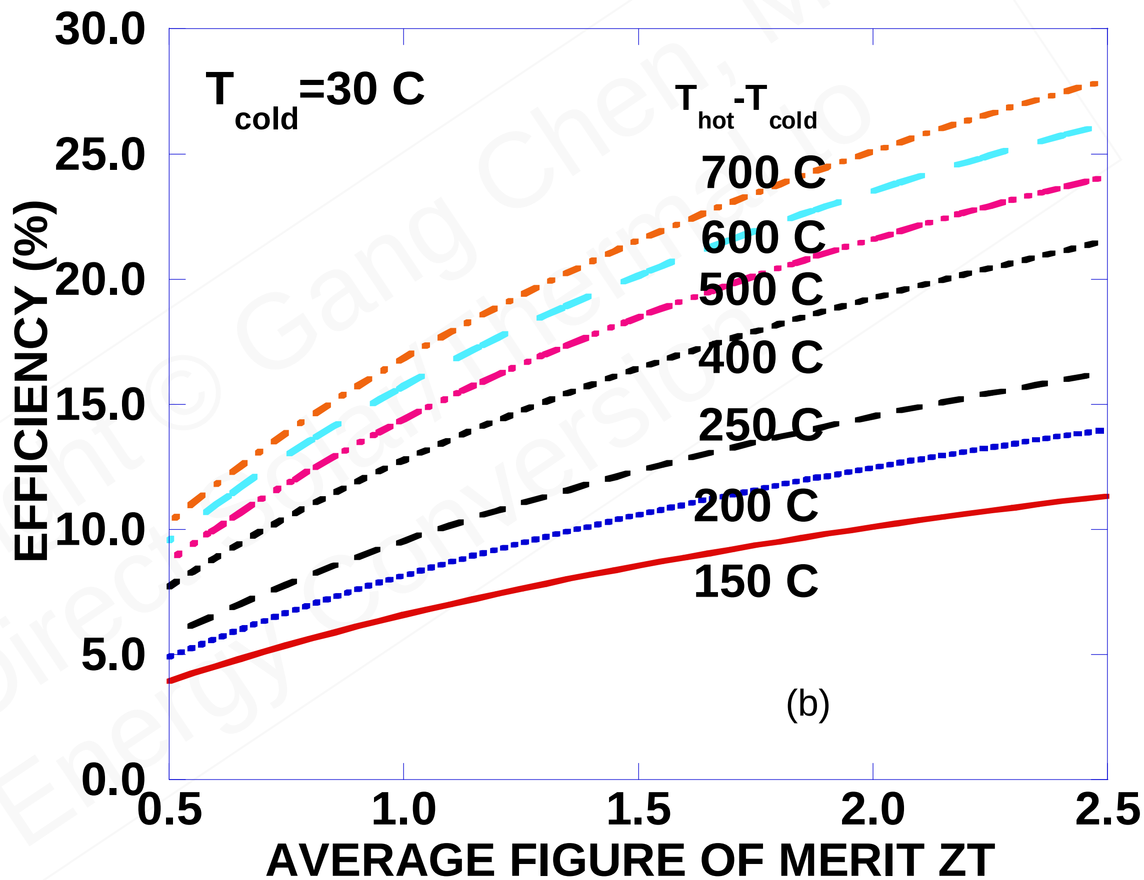
Solar Thermophotovoltaics



- Theoretical maximum efficiency: 85.4%; comparable to that of infinite number of multi-junction cells, but with only a single junction PV cell.
- Key Challenges: Selective surfaces absorbing solar radiation but re-emitting only in a narrow spectrum near the bandgap of photovoltaic cells, working at high temperatures.

Solar Thermoelectrics

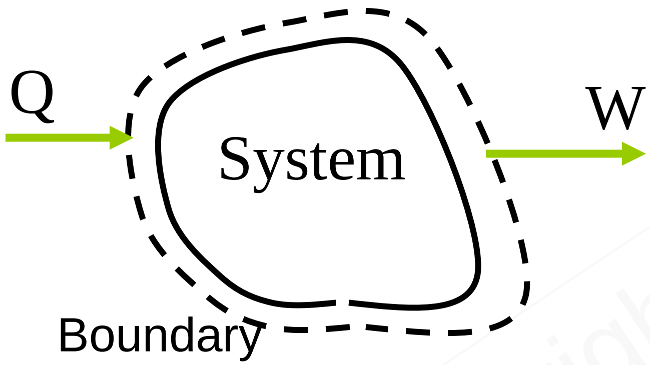




- **Low materials cost and low capital cost, potentially high efficiency.**
- **Key Challenges: Develop materials with high thermoelectric figure of merit; and selective surfaces that absorb solar radiation but do not re-radiative heat.**

1st Law of Thermodynamics

Environment



Closed:

$$E_2 - E_1 = Q_{12} - W_{12}$$

$$dE = \delta Q - \delta W$$

$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

State Properties: Process Independent

Process Dependent Quantities

Closed System
Open System

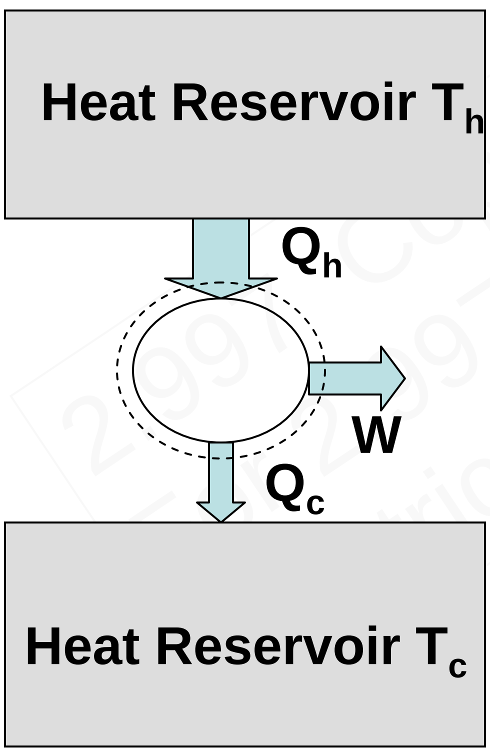
$$E = KE + PE + U \text{ (Internal Energy)} + \ldots$$

$$\text{Specific Heat } C = \frac{du}{dT} \text{ [J/K-kg, or J/K-m}^3\text{]}$$

2^{nd} Law of Thermodynamics

$$S_2 - S_1 = \oint \frac{\delta Q}{T_{boundary}} + S_{gen} \quad (S_{gen} \geq 0)$$

Entropy Change State Properties — **Entropy Transfer** — **Entropy Generation**



During a cycle:

$$\oint dS = 0$$

No entropy generation

$$0 = \frac{Q_h}{T_h} - \frac{Q_c}{T_c}$$

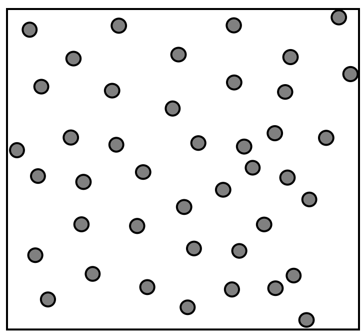
Maximum Efficiency (Carnot Efficiency)

$$\eta = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{T_c}{T_h}$$

T_h=223 ^oC, T_c=23 ^oC, η=40%
T_h=5800 K, T_c=300 K, η=95%
Thermal power plant η~40%, IC engines η~25%

Microscopic Picture of Entropy

- **For Isolated Systems**



Boltzmann Principle

$$S = k_B \ln \Omega$$

- **Microstate: a quantum mechanically allowed state**
- **A total of Ω microstate**
- **Principle of equal probability: each microstate is equally possible to be observed**

Probability $P = \dfrac{1}{\Omega}$

k_B=1.38x10^{-23} J/K ---Boltzmann constant

- **Constant Temperature and Closed Systems**

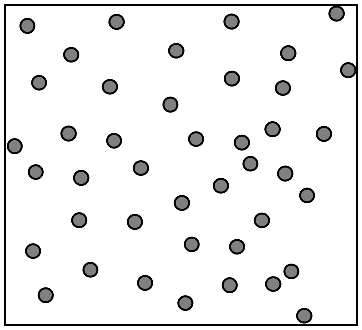
$$P(E) = Ae^{-E/(k_B T)}$$

- **Constant Temperature But Open Systems**

$$P(E) = Ae^{-(E-\mu)/(k_B T)}$$

μ --- chemical potential (driving force for mass diffusion); average energy needed to move a particle in/out off a system

Maxwell distribution



A box of gas molecules

$$E = \frac{1}{2} m\left(v_x^2 + v_y^2 + v_z^2\right)$$

$$P(v_x, v_y, v_z) = A \exp\left[\frac{m\left(v_x^2 + v_y^2 + v_z^2\right)}{2k_B T}\right]$$

All Probability must normalize to one

$$1 = \int_{-\infty}^{\infty} dv_x \int_{-\infty}^{\infty} dv_y \int_{-\infty}^{\infty} dv_z A \exp\left[\frac{m\left(v_x^2 + v_y^2 + v_z^2\right)}{2k_B T}\right] \Rightarrow A = \left(\frac{m}{2\pi k_B T}\right)^{3/2}$$

Maxwell Distribution

$$P(v_x, v_y, v_z) = \left(\frac{m}{2\pi k_B T}\right)^{3/2} \exp\left[\frac{m\left(v_x^2 + v_y^2 + v_z^2\right)}{2k_B T}\right]$$

One molecule

$$\langle E\rangle = \int_{-\infty}^{\infty} d\mathrm{v}_x \int_{-\infty}^{\infty} d\mathrm{v}_y \int_{-\infty}^{\infty} d\mathrm{v}_z \, \frac{1}{2} m\left(\mathrm{v}_x^2 + \mathrm{v}_y^2 + \mathrm{v}_z^2\right) A \exp\left[-\frac{m\left(\mathrm{v}_x^2 + \mathrm{v}_y^2 + \mathrm{v}_z^2\right)}{2k_B T}\right]$$

$$\langle E\rangle = \frac{3}{2} k_B T$$

Equipartition Principle: every quardratic term in microscopic energy contributes $k_B T/2$.

How much Is $k_B T$ at room temperature

$$k_B T = 1.38\times10^{-23}\ \mathrm{J/K}\times 300\mathrm{K} = 5.14\times10^{-21}\,J$$

$$= \frac{5.14\times10^{-21}\,J}{1.6\times10^{-19}\,J/eV} = 26\ \mathrm{meV}$$

Oxygen Atom at 300 K $\mathrm{v} = \sqrt{\frac{3k_B T}{m}} = \sqrt{\frac{3\times1.38\times10^{-23}\,J/K\times300K}{16\times1.67\times10^{-27}\,kg}} = 220\ \mathrm{m/s}$

Fermi-Dirac Distribution

- From quantum mechanics
  - Energy levels are quantized
  - Each quantum state can have maximum one electron
  - Planck-Einstein Relation
  - Planck constant h=6.6x10^{-34} Js, $\hbar = h/(2\pi)$

$$\text{Energy}: E = h\nu = \hbar\omega$$

$$\text{Momentum}: \text{p} = \text{h}/\lambda = \hbar \text{k}$$

- Consider one quantum state with an energy E at constant temperature T. The state can have zero electron (n=0) or one electron (n=1). What is the average number of electrons if one does many observations?

$$1 = \sum_{n=0,1} Ae^{-(E-\mu)/(k_B T)} = A\exp\left(\frac{\mu}{k_B T}\right)\left[1+\exp\left(-\frac{E}{k_B T}\right)\right]$$

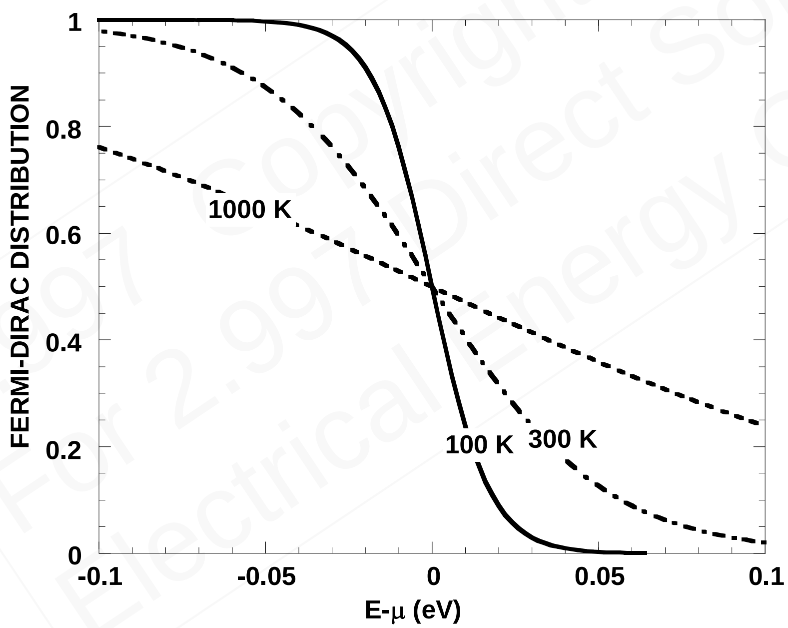
- Average number of electrons in the state

Fermi-Dirac Distribution

- **Average number of electrons in the state**

$$f = \sum_{n=0,1} nAe^{-(E-\mu)/(k_B T)} = \frac{1}{\exp\left(\frac{E-\mu}{k_B T}\right)+1}$$

Fermi-Dirac Distribution



At T=0K, μ is called Fermi level, E_f

F=1 for E<μ
F=0 for E>μ

Photons and Phonons

- From quantum mechanics
  - EM waves are quantized, basic energy quanta is called a photon
  - Photon has momentum
  - Planck-Einstein Relation
  - Each quantum state of photon (an EM wave mode) can have only integral number of photons

One Photon

$$\text{Energy}: E = h\nu = \hbar\omega$$

$$\text{Momentum}: \mathrm{p} = \mathrm{h}/\lambda = \hbar \mathrm{k}$$

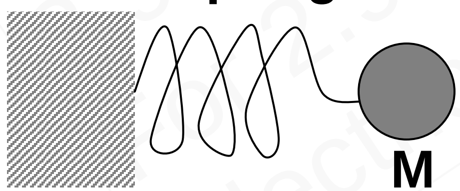
$$h = 6.6\times 10^{-34}\ \mathrm{Js};\ \hbar = h/(2\pi)$$

Energy of a quantum state:

$$E = \left(n + \frac{1}{2}\right)\hbar\omega \quad \mathrm{n} = 0, 1, 2\ldots$$

Zero point energy

- Classical Oscillator



Natural Frequency

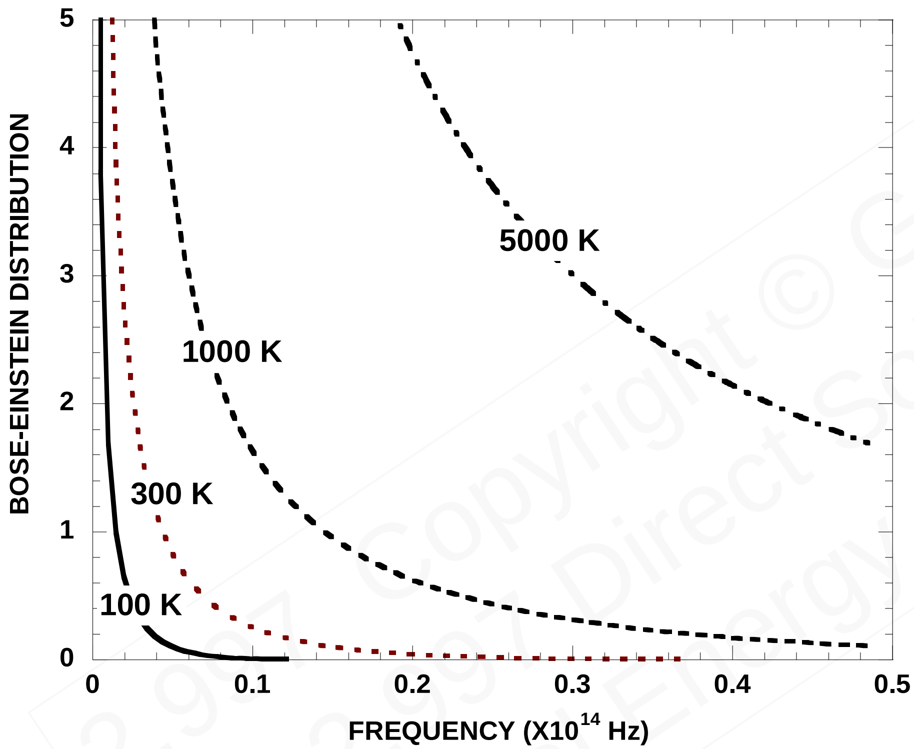
$$\nu = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$$

Energy of Mode

$$E = \left(n + \frac{1}{2}\right)\hbar\omega \quad \mathrm{n} = 0, 1, 2\ldots$$

Basic vibrational energy quanta hν is called a phonon

Bose-Einstein Distribution



- **Consider one quantum state in thermal equilibrium**

$$P(E_n) = Ae^{-(E_n-\mu)/(k_B T)}$$

- **Bose-Einstein Distribution**

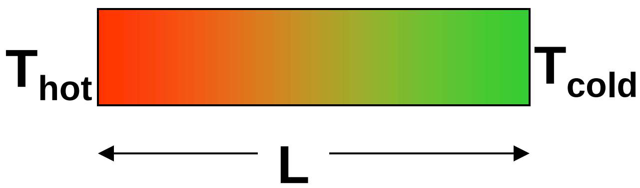
Average number of photons/phonons in one mode (quantum state)

$$f = \frac{1}{\exp\left(\dfrac{E-\mu}{k_B T}\right) - 1}$$

Usually μ=0

Heat Transfer Modes

Heat Conduction



- **Fourier Law**

$$\dot{Q} = -kA\frac{dT}{dx}\ [\mathrm{W}]$$

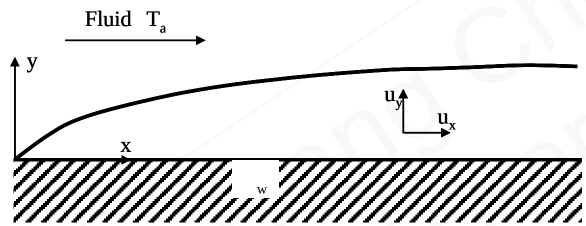
Thermal Conductivity [W/m-K] Materials Property (k)

Cross-Sectional Area (A)

- **Heat Flux**

$$\dot{q} = -k\frac{dT}{dx}\ (= -k\nabla T)\ \left[\mathrm{W/m^2}\right]$$

Convection



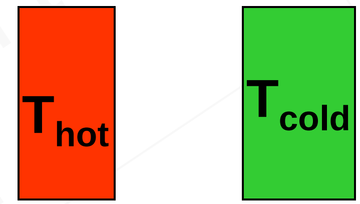
- **Newton's law of cooling**

$$\dot{Q} = hA\left(T_w - T_a\right)$$

Convective Heat Transfer Coefficient [W/m²K] Flow dependent (h)

- **Natural Convection**
- **Forced Convection**

Thermal Radiation



- **Stefan-Boltzmann Law for Blackbody**

$$\dot{Q} = A\sigma T^4$$

Stefan-Boltzmann Constant
$\sigma = 5.67\times10^{-8}\ \mathrm{W/m^2K^4}$

- **Heat transfer**

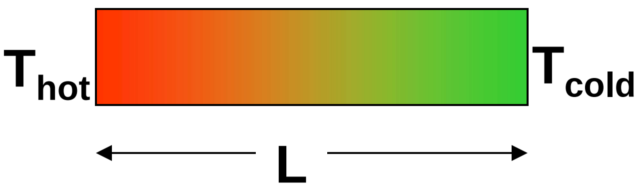
$$\dot{Q} = AF\ \varepsilon\sigma\left(T_{hot}^{\ 4} - T_{cold}^{\ 4}\right)$$

View factor F=1 for two parallel plates (F)

Emissivity of two surfaces (ε)

Heat Conduction

Heat Conduction

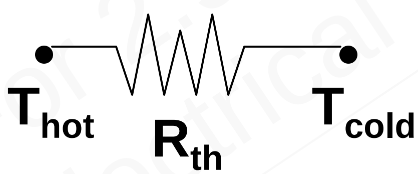


1D, no heat generation

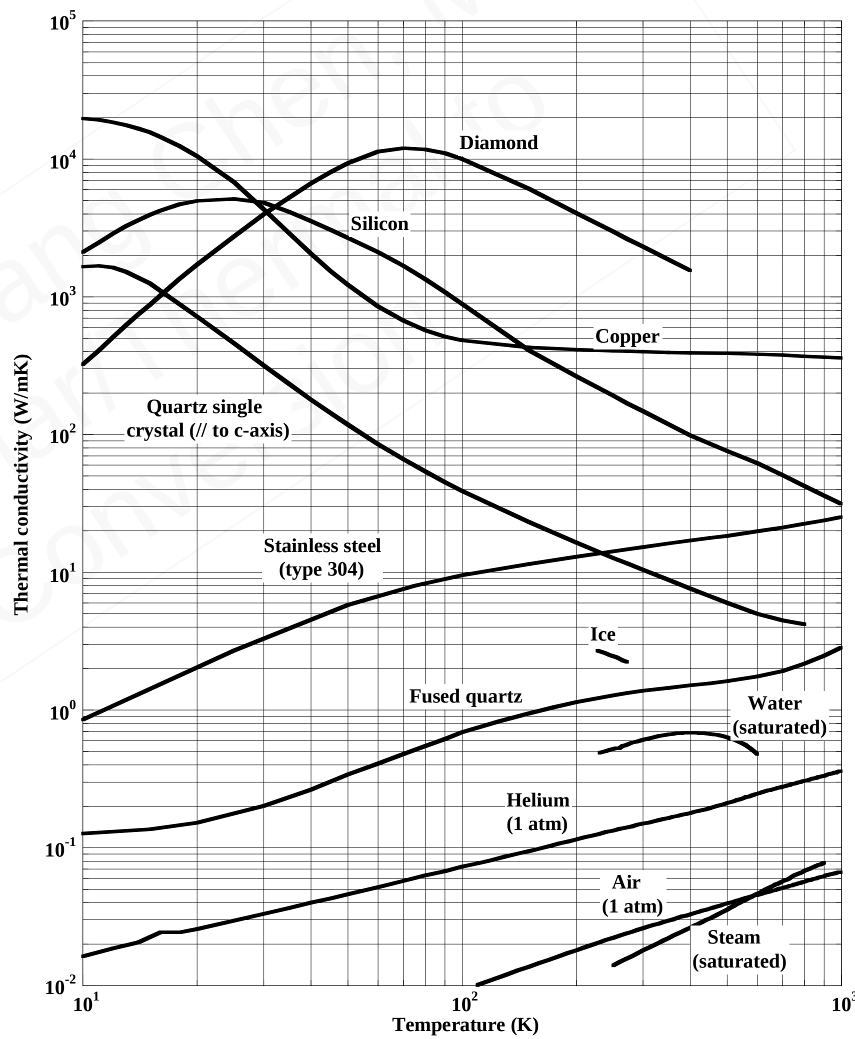
$$\dot{Q} = kA\frac{T_{hot} - T_{cold}}{L} = \frac{T_{hot} - T_{cold}}{R_{th}}$$

Thermal Resistance $R_{th} = \frac{L}{kA}$

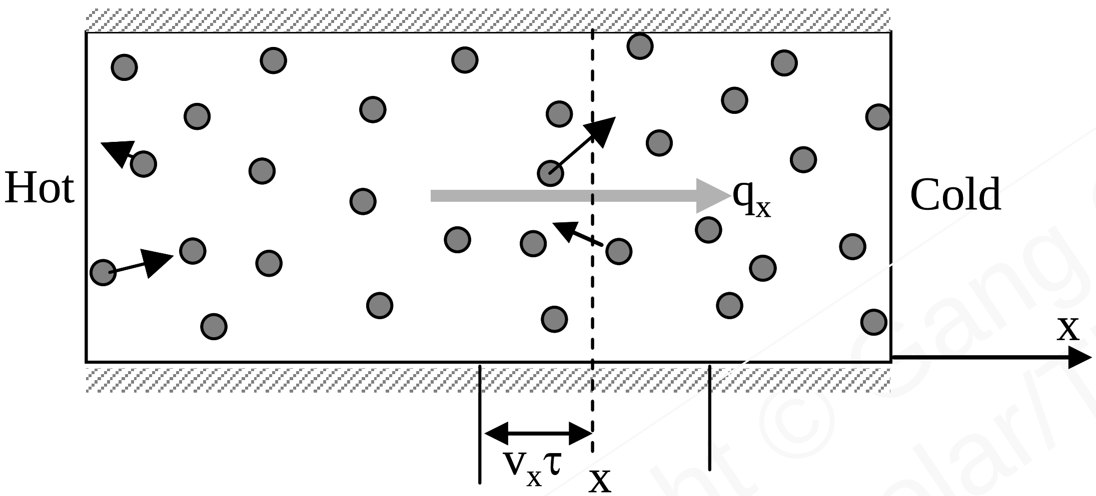
Heat Current $\dot{Q}$



Convection $R_{th} = \frac{1}{hA}$



Heat Conduction: Kinetic Picture



$$q_x = \frac{1}{2}\left(nEv_x\right)\Big|_{x-v_x\tau} - \frac{1}{2}\left(nEv_x\right)\Big|_{x+v_x\tau}$$

$$q_x = -v_x\tau\frac{d(Env_x)}{dx} = -\frac{v^2\tau}{3}\frac{dU}{dT}\frac{dT}{dx}$$

$$= -\frac{v^2\tau}{3}C\frac{dT}{dx} = -k\frac{dT}{dx}$$

Thermal Conductivity $\quad k = \frac{1}{3}Cv\Lambda$

- **Energy per particle: E [J]**
- **Number of particles per unit volume: n [1/m³]**
- **Average random velocity of particles v**
- **Average time between collision of two particles τ---relaxation time**
- **Average distance travelled between collision Λ=vτ---Mean free path**
- **Volumetric specific heat**

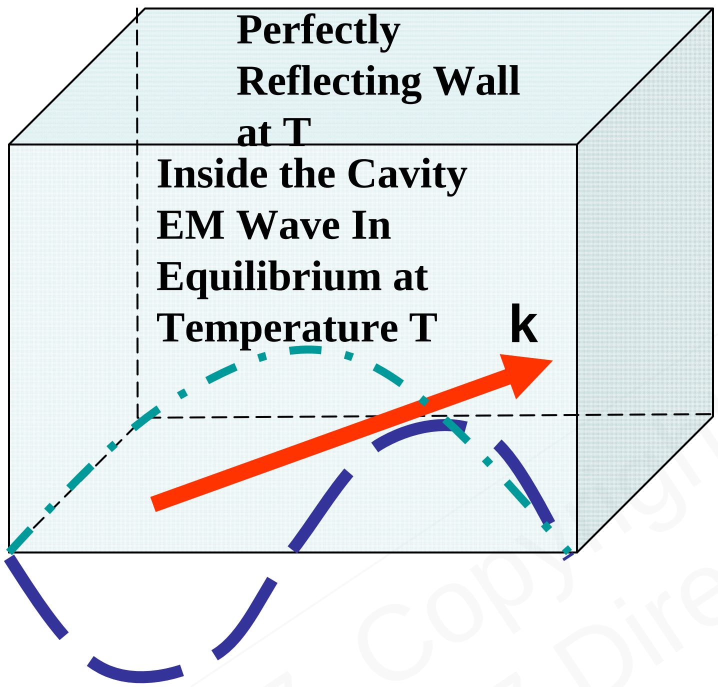
$$C = \frac{dU}{dT}\left[\mathrm{J}/\mathrm{m}^3K\right]$$

$$C = \rho c$$

Density

Specific heat per unit mass

Thermal Radiaton: Planck's Law



$$L_x = \frac{\lambda_x}{2}, 2\frac{\lambda_x}{2}, \ldots, n_x\frac{\lambda_x}{2}, \ldots$$

$$k_x = n_x \frac{2\pi}{2L_x}$$

Two polarization

Basic Relations

Frequency ν
Angular Frequency ω=2πν
Wavelength λ
Wavevector magnitude k=2π/λ
Wavevector **k**=(k_x,k_y,k_z)

$$c = \nu\lambda \quad \Rightarrow \quad \omega = ck = c\sqrt{k_x^2 + k_y^2 + k_z^2}$$

ω(k): Dispersion relation (linear)

How much energy in the cavity?

$$U = 2\sum_{n_x=1}^{\infty}\sum_{n_y=1}^{\infty}\sum_{n_z=1}^{\infty}\hbar\omega f(\omega,T) =$$

$$2\int_0^{\infty}\frac{dk_x}{(2\pi/2L_x)}\int_0^{\infty}\frac{dk_y}{(2\pi/2L_y)}\int_0^{\infty}\frac{dk_z}{(2\pi/2L_z)}\hbar\omega f(\omega,T)$$

$$= 2\int_{-\infty}^{\infty}\frac{dk_x}{(2\pi/L_x)}\int_{-\infty}^{\infty}\frac{dk_y}{(2\pi/L_y)}\int_{-\infty}^{\infty}\frac{dk_z}{(2\pi/L_z)}\hbar\omega f(\omega,T)$$

Thermal Radiaton: Planck's Law

$$U = \frac{2V}{8\pi^3} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \hbar\omega f(\omega,T) dk_x dk_y dk_z$$

$$= \frac{2V}{8\pi^3} \int_0^{\infty} \hbar\omega f(\omega,T) 4\pi k^2 dk$$

$$= \frac{2V}{8\pi^3} \int_0^{\infty} \hbar\omega f(\omega,T) 4\pi \left(\frac{\omega}{c}\right)^2 d\left(\frac{\omega}{c}\right)$$

$$\frac{U}{V} = \int_0^{\infty} \hbar\omega f(\omega,T) \frac{\omega^2}{\pi^2 c^3} d\omega$$

$$= \int_0^{\infty} \hbar\omega f(\omega,T) D(\omega) d\omega$$

$$= \int_0^{\infty} u(\omega) d\omega$$

D(ω)-density of states per unit volume per unit angular frequency interval

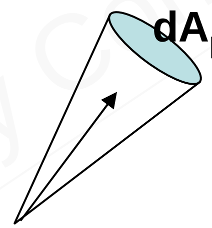
- **Energy density per ω interval**

$$u(\omega) = \hbar\omega f(\omega,T) D(\omega)$$

$$= \frac{\hbar\omega^3}{\pi^2 c^3} \frac{1}{\exp\left(\frac{\hbar\omega}{k_B T}\right) - 1}$$

Planck's law

- **Intensity: energy flux per unit solid angle**



$$I(\omega) = \frac{c u(\omega)}{4\pi} = \frac{\hbar\omega^3}{4\pi^3 c^2} \frac{1}{\exp\left(\frac{\hbar\omega}{k_B T}\right) - 1}$$

Solid Angle

$$d\Omega = \frac{dA_p}{R^2}$$

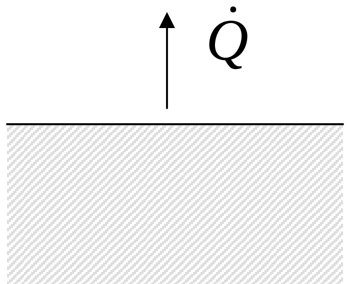
whole space 4π

Per unit wavelength interval

$$I(\lambda) = \left|\frac{I(\omega) d\omega}{d\lambda}\right| = \frac{4\pi c\hbar}{\lambda^5} \frac{1}{\exp\left(\frac{2\pi\hbar c}{k_B T \lambda}\right) - 1}$$

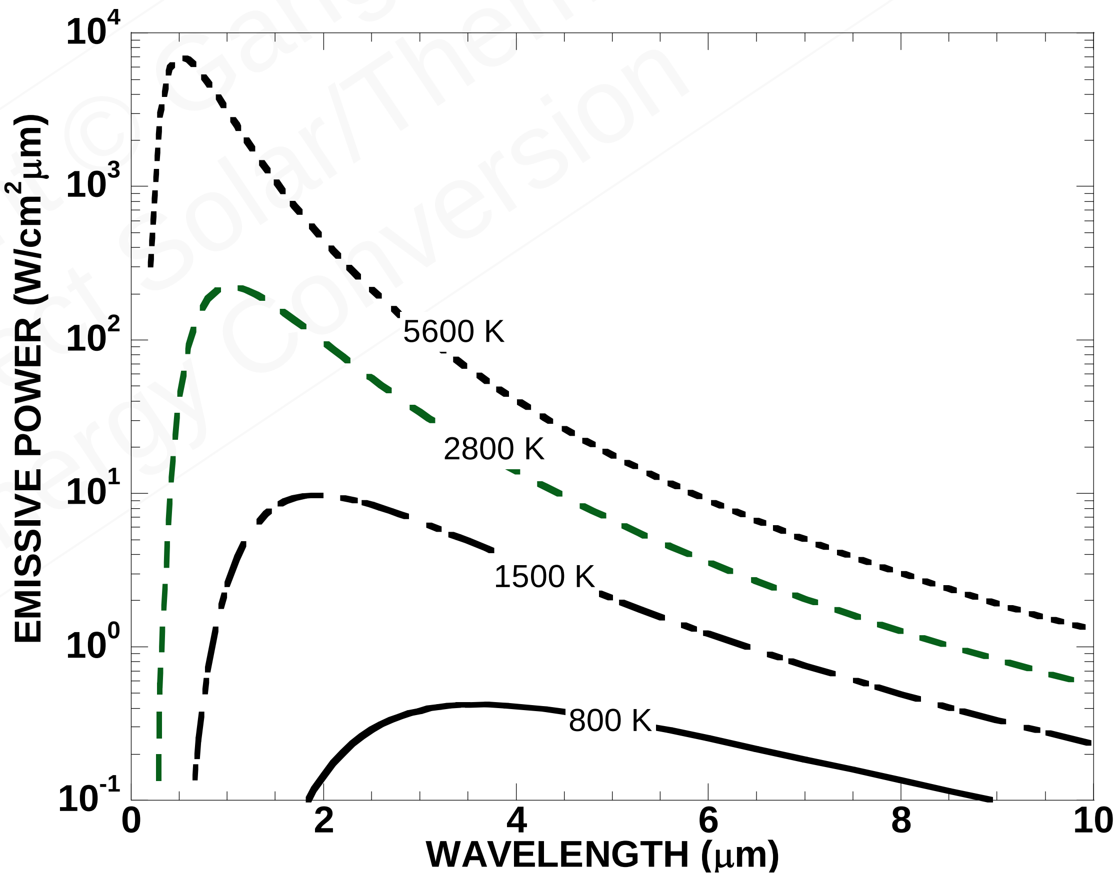
Planck's law

Thermal Radiaton: Planck's Law



Wien's displacement law

$$\lambda_{\max} T = 2898 \ \text{K}\mu\text{m}$$



Emissive Power

$$\dot{Q}(\lambda) = A\pi I(\lambda)$$

$$= A\frac{\hbar\omega^3}{4\pi^2 c^2}\frac{1}{\exp\left(\frac{\hbar\omega}{k_B T}\right)-1}$$

Total

$$\dot{Q} = \int_0^\infty \dot{Q}(\lambda)d\lambda = A\sigma T^4$$

2.997 Direct Solar/Thermal to Electrical Energy Conversion Technologies
Fall 2009