Thermal Physics

Lecture 7 – Energy Transfer Mechanisms

Very unsafe liquid nitrogen bottle rockets!   Youtube.com/Fysikshow

Last lecture...

- **Adiabatic processes** involve no heat transfer.

$$Q = 0$$

- An adiabatic process satisfies the PV-relation:

$$PV^\gamma = \text{constant}$$

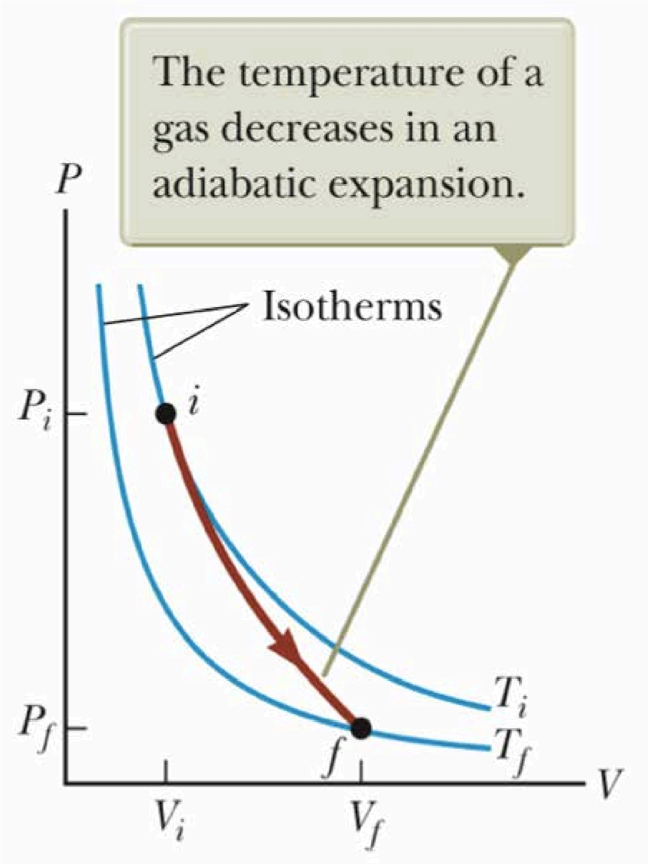
  - where

$$\gamma = \frac{c_P}{c_V}$$

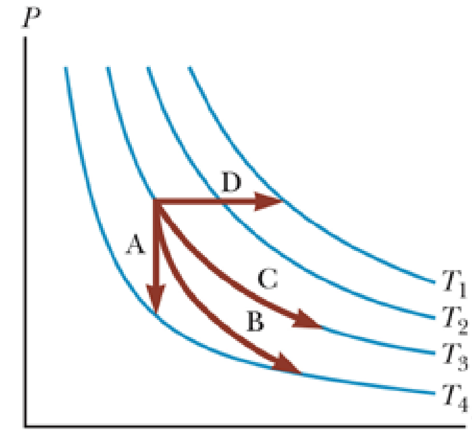
Molar specific heats

$$c_V = \frac{f}{2} R$$

$$c_P = c_V + R$$



Special paths review



- **Isothermal** constant temperature

$$PV = \text{constant} \qquad \Delta E_{int} = 0$$

- **Isobaric** constant pressure

$$\frac{T}{V} = \text{a constant} \qquad Q = nC_P \Delta T$$

- **Isovolumetric** constant volume

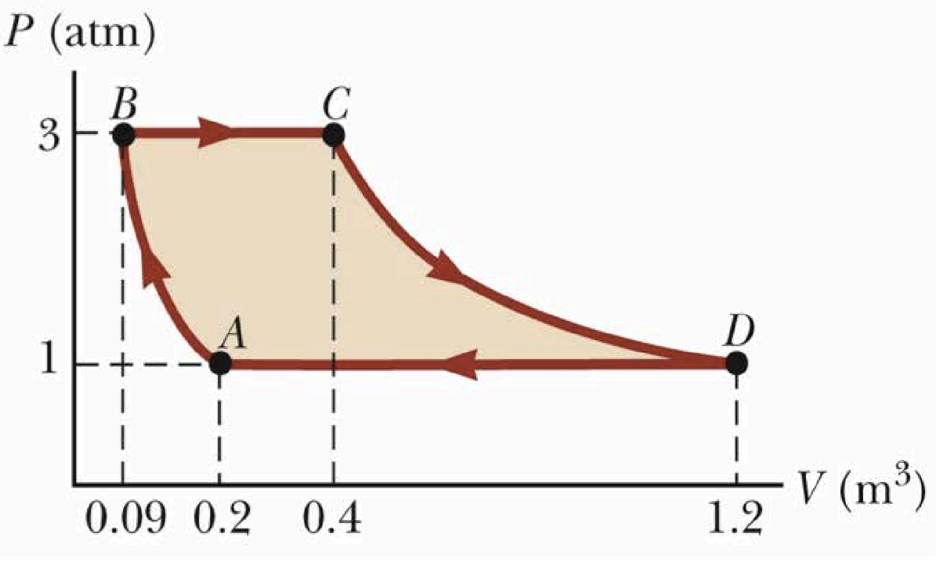
$$\frac{P}{T} = \text{constant} \qquad \Delta E_{int} = Q = nC_V \Delta T$$

Last lecture...

- **Cyclic** processes (processes that start and end in the same state):

$$\Delta E_{int}^{cycle} = 0$$

$$Q^{\text{cycle}} = -W^{\text{cycle}}$$



Phase Changes

Phase Changes

- A **phase change** is when a substance changes from one form to another
  - Two common phase changes are
    - Solid to liquid (melting)
    - Liquid to gas (boiling)
- During a phase change, the internal structure and energy of a material change but there is <u>no change</u> in temperature of the substance
- We describe the amount of energy required to effect the change by the “Latent Heat”

Latent Heat, *L*

- Different substances react differently to the energy added or removed during a phase change due to their different molecular arrangements
- The amount of energy also depends on the mass of the sample
- If an amount of energy Q is required to change the phase of a sample of mass m, then $L = Q/m$

Latent Heat, cont

- The quantity *L* is called the **latent heat** of the material
  - Latent means “hidden”
  - The value of *L* depends on the substance as well as the actual phase change
- The energy required to change the phase is

$$Q = \pm \mathrm{D}mL$$

+ sign if going UP in phase (solid à liquid à gas)

- sign if going DOWN in phase (gas à liquid à solid)

Latent Heat, final

- The *latent heat of fusion* is used when the phase change is from solid to liquid
- The *latent heat of vaporisation* is used when the phase change is from liquid to gas
- The positive sign is used when the energy is transferred into the system
  - This will result in melting or boiling
- The negative sign is used when energy is transferred out of the system
  - This will result in freezing or condensation

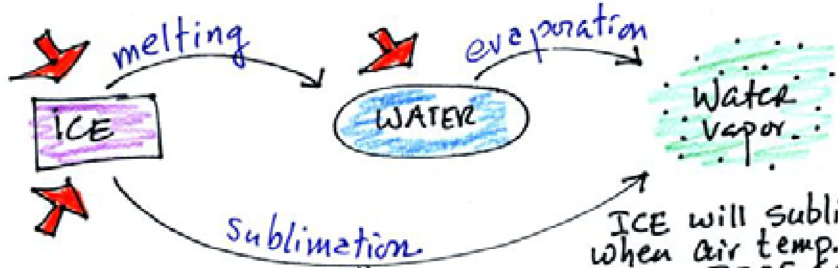
Table 19.3
Latent heats of fusion and vaporisation

Substance	Melting point (°C)	Latent heat of fusion	Boiling point (°C)	Latent heat of vaporisation (J/kg)
Helium	−269.65	5.23×10^3	−268.93	2.09×10^4
Oxygen	−218.79	1.38×10^4	−182.97	2.13×10^5
Nitrogen	−0.97	2.55×10^4	−195.81	2.01×10^5
Alcohol, ethyl	−114	1.04×10^5	78	8.54×10^5
Water	0.00	3.33×10^5	100.00	2.26×10^6
Sulfur	119	3.81×10^4	444.60	3.26×10^5
Lead	327.3	2.45×10^4	1750	8.70×10^5
Aluminium	660	3.97×10^5	2450	1.14×10^7
Silver	960.80	8.82×10^4	2193	2.33×10^6
Gold	1063.00	6.44×10^4	2660	1.58×10^6
Copper	1083	1.34×10^5	1187	5.06×10^6

ENERGY TRANSPORT in the FORM of LATENT HEAT

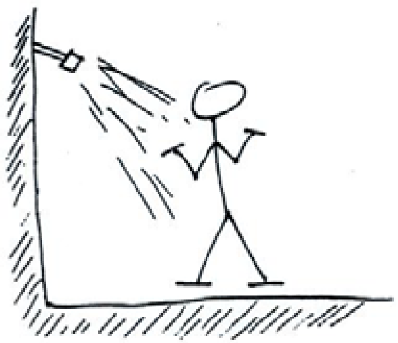
consciously ADD ENERGY (place material in a pan, put on a hot stove)

(needed energy may be taken from surroundings)



ICE will sublimate when air temp. is below 32°F (0°C).

example: dry ice (solid CO_2)



Phase changes sometimes occur "whether we want them to or not." They still require energy & take it from their surroundings.

Step out of a shower. Water evaporates. Needed energy is taken from your body – you feel cold.

http://www.atmo.arizona.edu/students/courselinks/fall07/nats101s31/lecture_notes/sep27.html

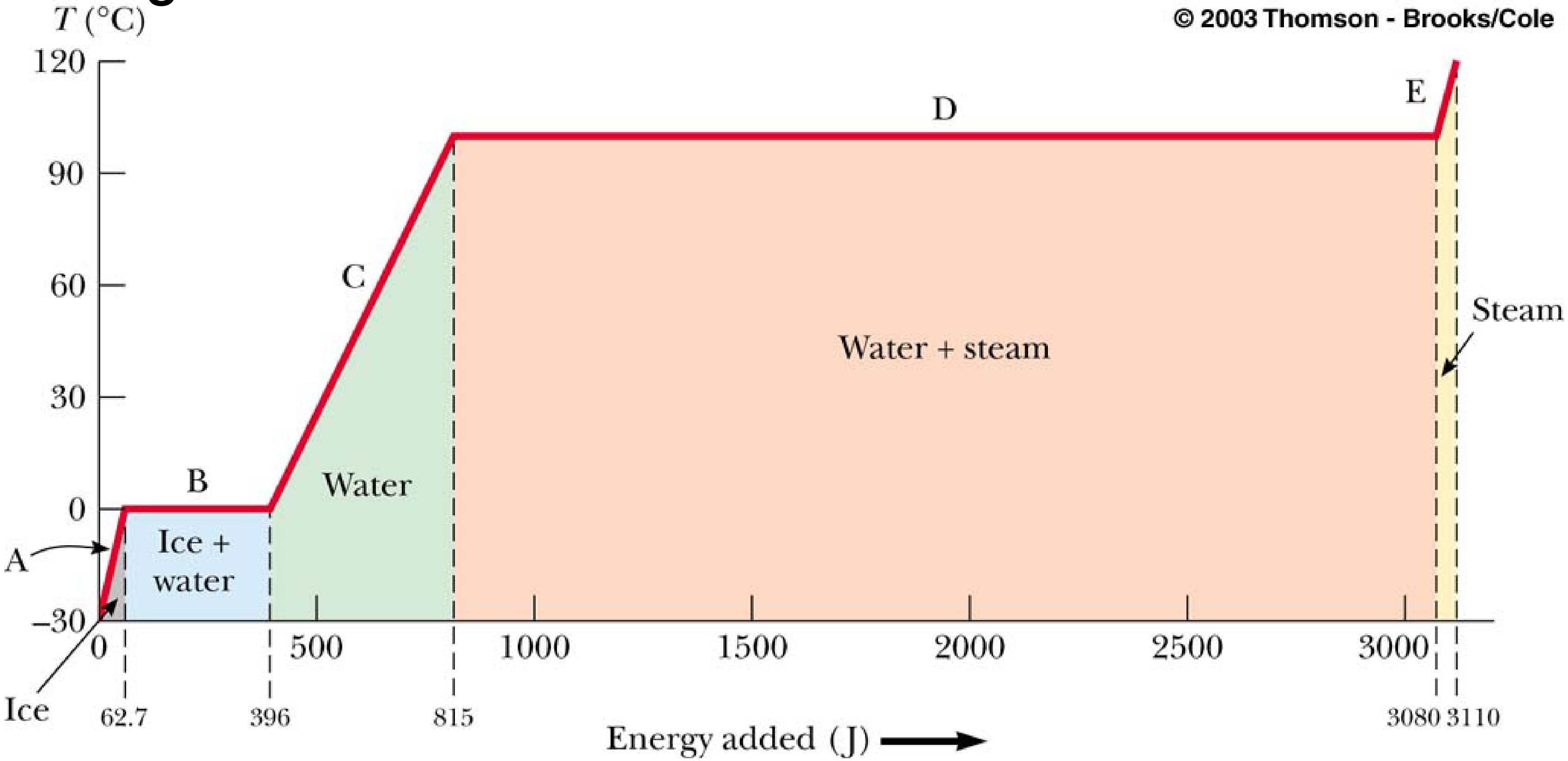
Question

The highest waterfall in the world is the Salto Angel Falls in Venezuela. Its longest fall has a height of 807 m. If water at the top of the falls is at 15.0 ^{o}C, what is the maximum temperature of water at the bottom of the falls? Assume all the kinetic energy of the water as it reaches the bottom goes into raising the temperature.

$$Q = mc\Delta T$$

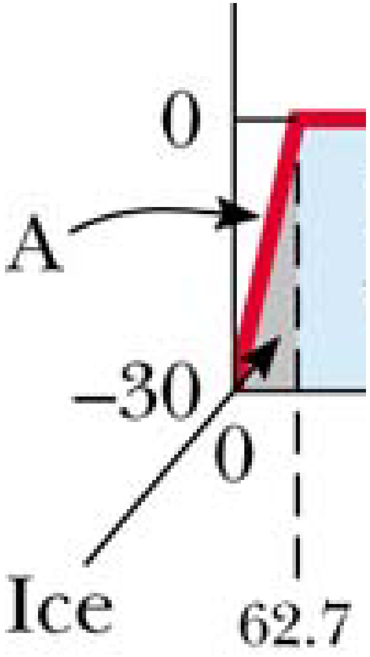
From Ice to Steam in 5 parts

- How much energy do you need to turn 1 g of ice of -30 ºC into steam of 120 ºC?



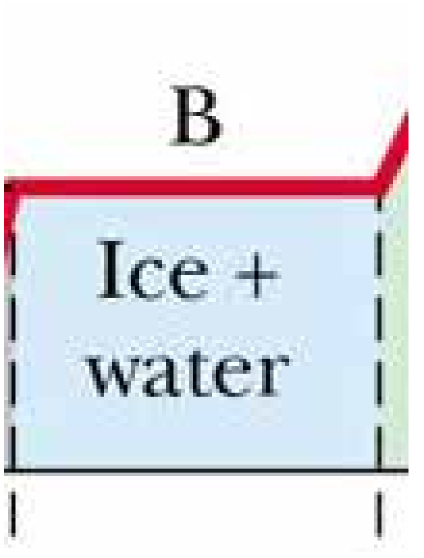
Part A: Warming Ice

- Start with one gram of ice at –30.0ºC
- During phase A, the temperature of the ice changes from –30.0ºC to 0ºC
- Use $Q = m_i c_i \Delta T$
  – Find (exercise) that 62.7 J of energy are added



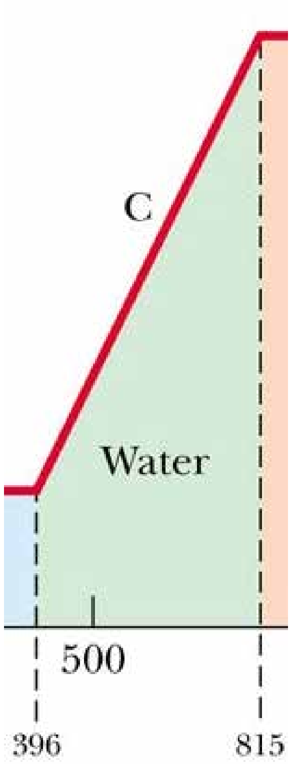
Part B: Melting Ice

- Once at 0ºC, the phase change (melting) starts
- The temperature stays the same although energy is still being added
- Use $Q = m_i L_f$
  - Exercise: find the energy required is 333 J L_f = 334774 J/kg C
  - On the graph, the values move from 62.7 J to 396 J



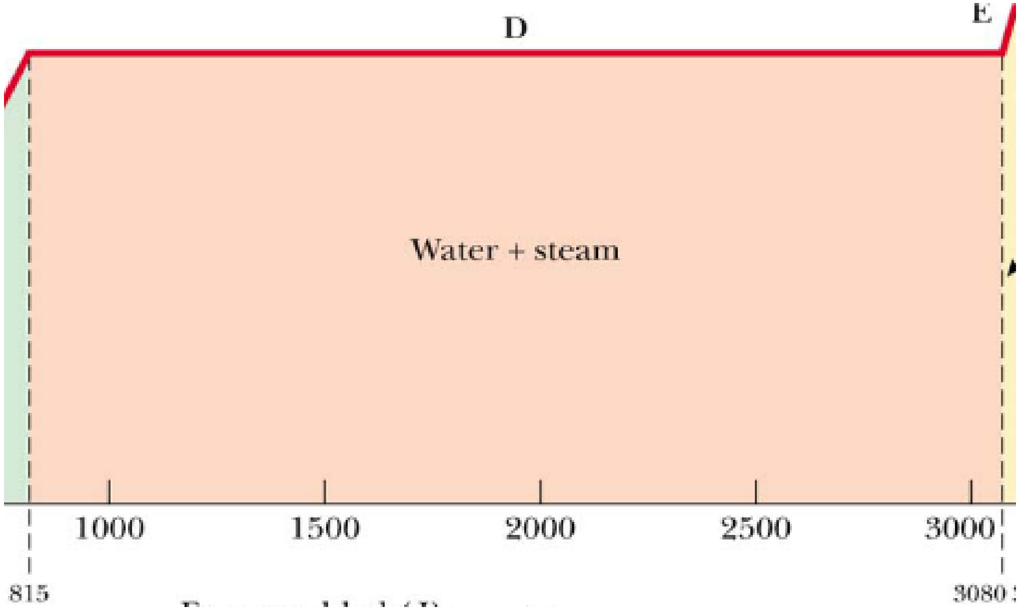
Part C: Warming Water

- Between 0ºC and 100ºC, the material is liquid and no phase changes take place
- Energy added increases the temperature
- Use $Q = m_w c_w \Delta T$
  - Exercise: find that 419 J are added
  - The total energy added is now 815 J



Part D Boiling Water

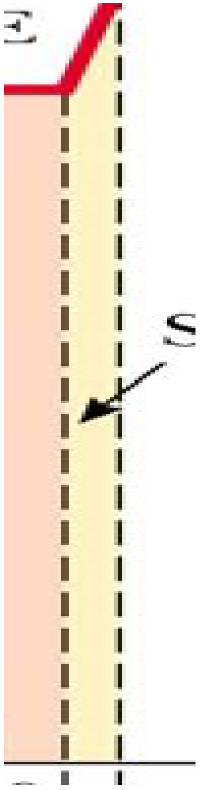
- At 100ºC, a phase change occurs (boiling)
- Temperature does not change
- Use $Q = m_w L_v$
  - Exercise: find this requires 2260 J
  - Lv = 2.26×10^6 J/kg C
  - The total is now 3070 J



Note that the transition to steam dominates the total amount of energy required in all the 5 parts.

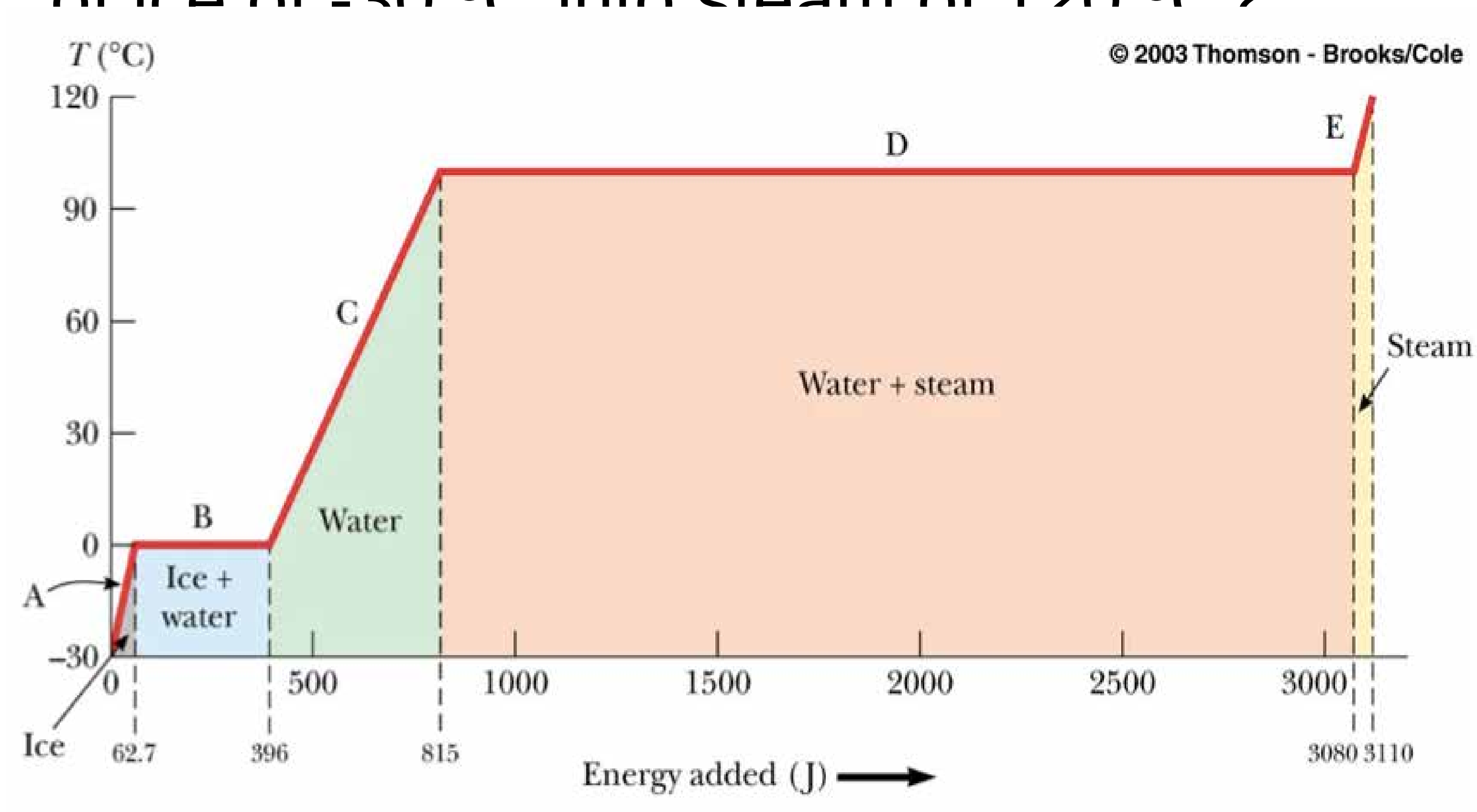
Part E: Heating Steam

- After all the water is converted to steam, the steam will heat up
- No phase change occurs
- The added energy goes to increasing the temperature
- Use $Q = m_s c_s \Delta T$
  - Exercise: find that 40.2 J are needed
  - The temperature rises to 120º C
  - The total energy added is 3110 J



From ice to steam...

- How much energy do you need to turn 1 g of ice of -30 ºC into steam of 120 ºC?



Problem solving strategies...

- Units of measurement must be consistent
  - e.g., if c is given in J/kg.ºC, then your mass must be in kg, the temperatures in ºC and energies in J.
- Transfers of energy:
  - $Q = mc\Delta T$ when no phase transition occurs.
  - $Q = mL$ for each phase transition.
- ΔT is always $T_{\mathrm{final}} - T_{\mathrm{initial}}$.
- Energy transfer to a system is $+Q$.
- Energy removed from a system is $-Q$.

Superheating

Superheating and cooling

- A phase change needs a disturbance or "nucleation site" to take place.
- Water heated in the microwave can get above 100^{o}C as it is kept still. When removed it will suddenly boil.
- It is also possible to supercool water.
- Adding mentos to coke provides nucleation sites for the dissolved CO_2 to leave the coke.

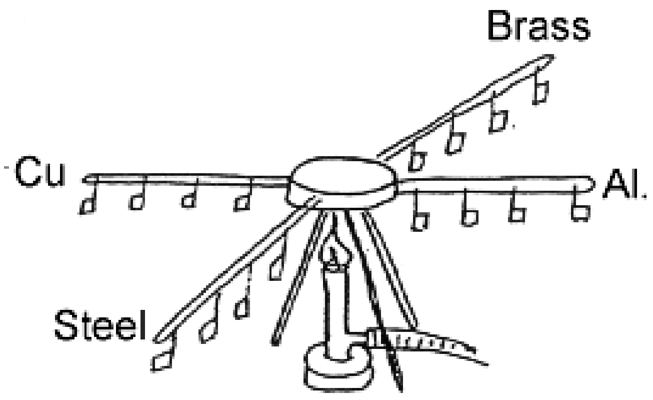
You knew this was coming

Wrap up and on to next topic

Demo Unit Hb10: thermal conductivity

- When the centre block is heated the different rates of thermal conductivity are shown by the rate that the flags, which are attached with wax, drop.

Material	k W/m/°C
Cu	397
Al	237
Brass	109
Steel	40

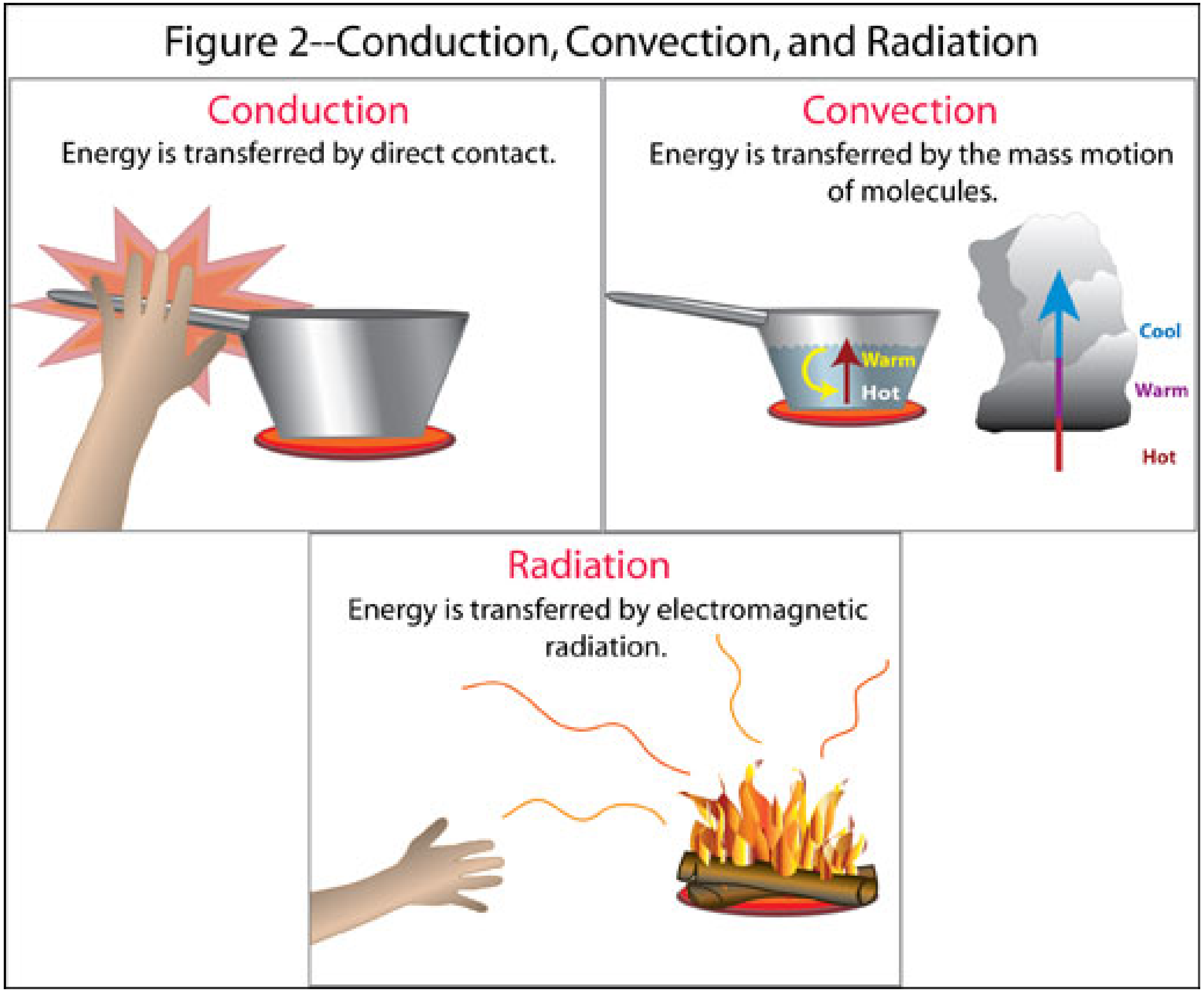


Heat transfer...

- We have talked a lot about heat entering and leaving a system.
  - But how exactly does heat transfer happen?
  - There are **three** mechanisms:
    - **Conduction**
    - **Convection**
    - **Radiation**

Three methods of heat transfer

we want to know the rate of energy transfer for each



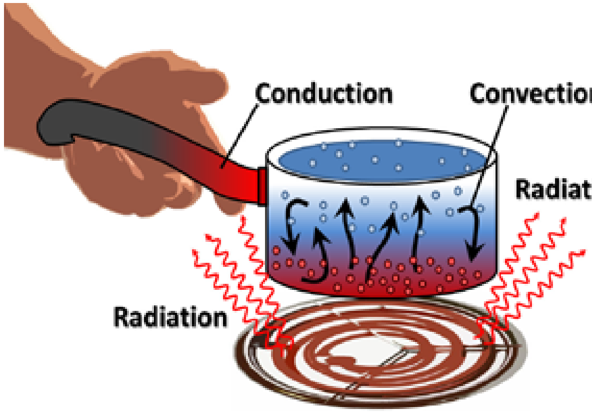
Heat transfer>Conduction...

View heat transfer on atomic scale

- Microscopic particles (atoms/molecules/electrons) in one part of the object acquire more energy.
- They collide with neighbouring particles
- Less energetic particles gain energy during collisions with more energetic particles
- The neighbouring particles collide with their neighbouring particles, and so on, until energy is spread over the whole object.
- Rate of conduction depends on the characteristic of the material.

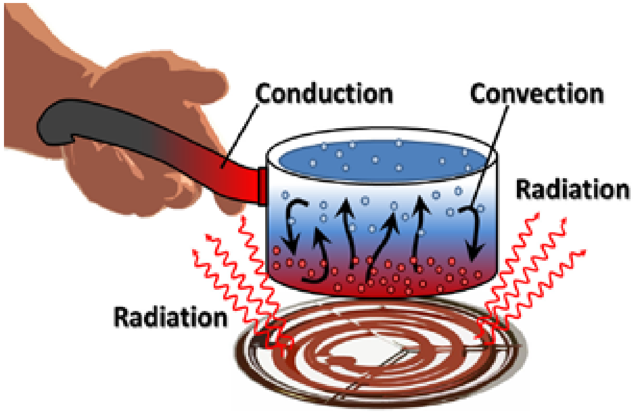
Heat transfer>Conduction...

- **Metals** are good conductors of heat.
  - They contain large numbers of electrons that are relatively free to move through the metal.
- **Glass, paper, asbestos**, ... are poor conductors of heat.
  - They contain far fewer free particles.
- **Gases** are poor conductors.
  - Although the particles move freely, the interparticle spacing is large compared with solids.
  - Collisions are not as frequent.



Heat transfer>Conduction...

- Conduction happens only when there is a temperature difference.
  - If the microscopic particles in different parts of an object have, on average, the same energy, then the **net energy transferred during collisions is zero**.



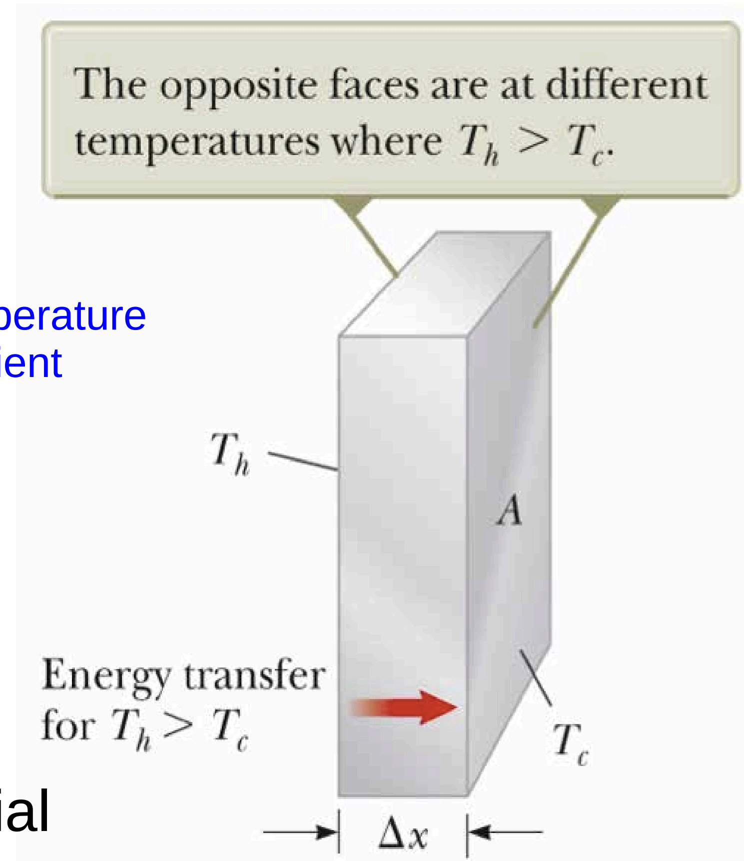
Demo Unit Hb6: thermal conductivity

- Wood and metal rod + FIRE
- Does the paper burn?

Heat transfer>Thermal conductivity...

- Conduction happens only when there is a temperature difference.

- Energy transfer per unit time (J/s = power in Watts):



Temperature difference

Temperature gradient

$$P_{\text{cond}} = \kappa A \left(\frac{\Delta T}{\Delta x} \right) = \kappa A \left(\frac{dT}{dx} \right)$$

Cross-sectional area

Thickness of slab

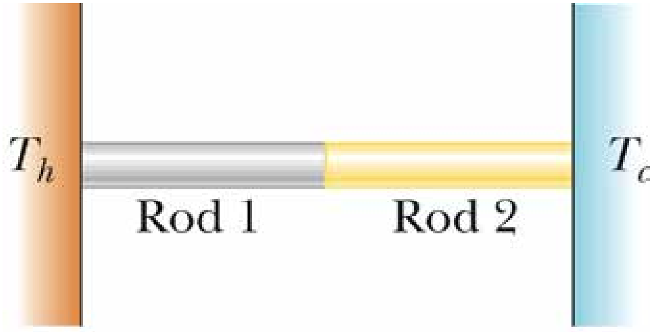
- κ = Thermal conductivity of the material
- Good conductors have high κ values and good insulators have low κ values

Conduction, equation explanation

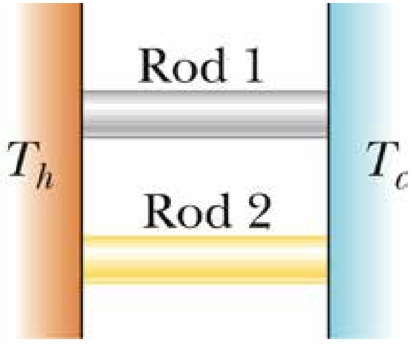
$$P = \kappa A \left| \frac{dT}{dx} \right|$$

- *A* is the cross-sectional area
- Δx is the thickness of the slab
  - Or the length of a rod
- *P* is in Watts when *Q* is in Joules
- *k* is the *thermal conductivity* of the material
  - Good conductors have high *k* values and good insulators have low *k* values

Quick Quiz



(a)



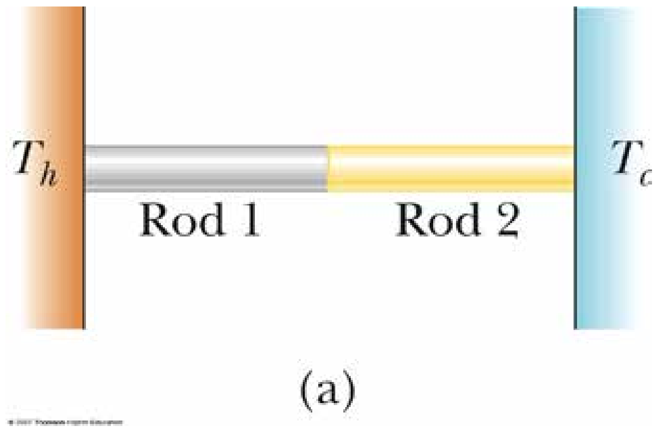
(b)

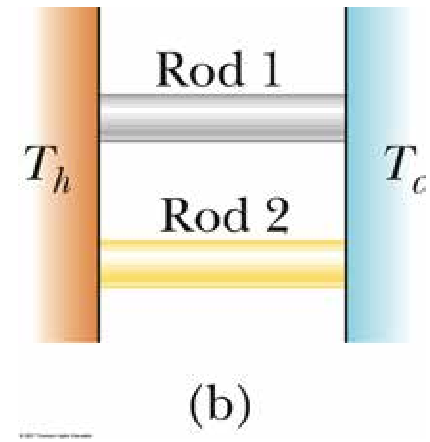
- In which case is the rate of energy transfer by heat larger?

- (a) When the rods are in Series
- (b) When the rods are in Parallel

Quick Quiz

$$P = \kappa A \frac{T_h - T_c}{L}$$





- In which case is the rate of energy transfer by heat larger?

- (a) When the rods are in Series
- **(b) When the rods are in Parallel**
- *In Parallel, as the rods present a larger cross-sectional area for heat to flow through, as well as a smaller length for it to pass along.*

Some Thermal Conductivities

Substance	Thermal Conductivity (W/m · °C)
Metals (at 25°C)	
Aluminum	238
Copper	397
Gold	314
Iron	79.5
Lead	34.7
Silver	427
Gases (at 20°C)	
Air	0.023 4
Helium	0.138
Hydrogen	0.172
Nitrogen	0.023 4
Oxygen	0.023 8

Substance	Thermal Conductivity (W/m · °C)
Nonmetals (approximate values)	
Asbestos	0.08
Concrete	0.8
Diamond	2 300
Glass	0.8
Ice	2
Rubber	0.2
Water	0.6
Wood	0.08

Heat transfer>Thermal conductivity...

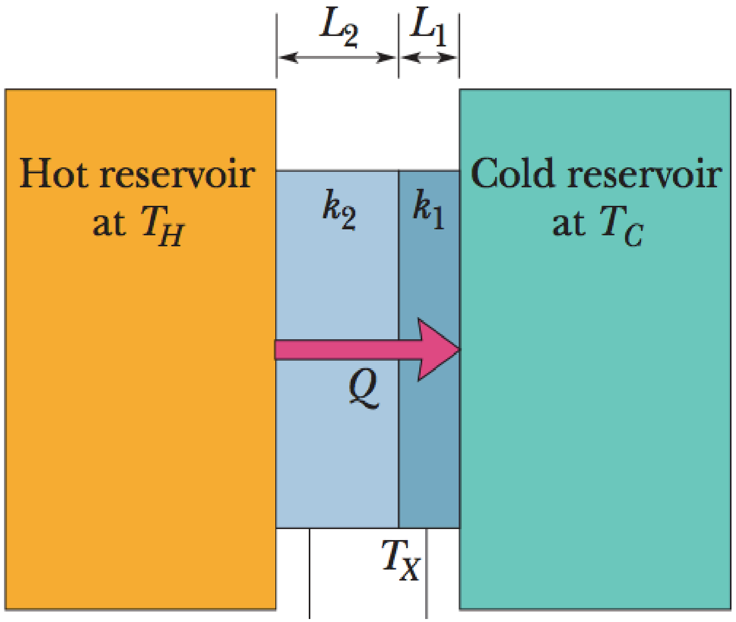
- Sometimes the conducting object is a composite of two different materials in series.
  - What is the steady state heat transfer rate?

BLACKBOARD

$$P_{\mathrm{cond}} = \frac{A\left(T_H - T_C\right)}{\sum_i R_i}$$

$$R_i = \frac{L_i}{\kappa_i}$$

R-value of material i



Steady state = equal energy transfer rate in the two slabs.

Compound Slab

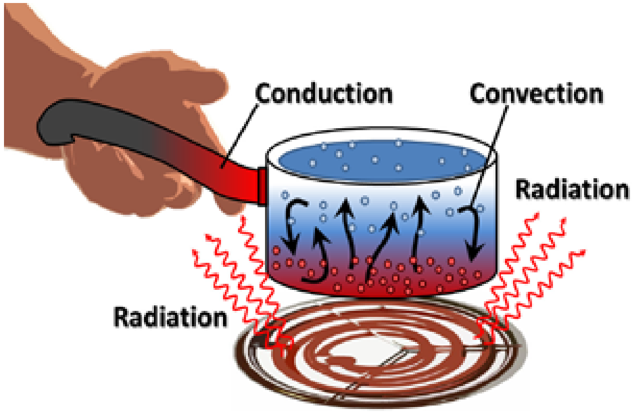
- For a compound slab containing several materials of various thicknesses (L_1, L_2, ...) and various thermal conductivities (k_1, k_2, ...) the rate of energy transfer depends on the materials and the temperatures at the outer edges:

$$\wp = \frac{A\left(T_h - T_c\right)}{\sum_i \left(L_i / k_i\right)}$$

Heat transfer 2>Convection...

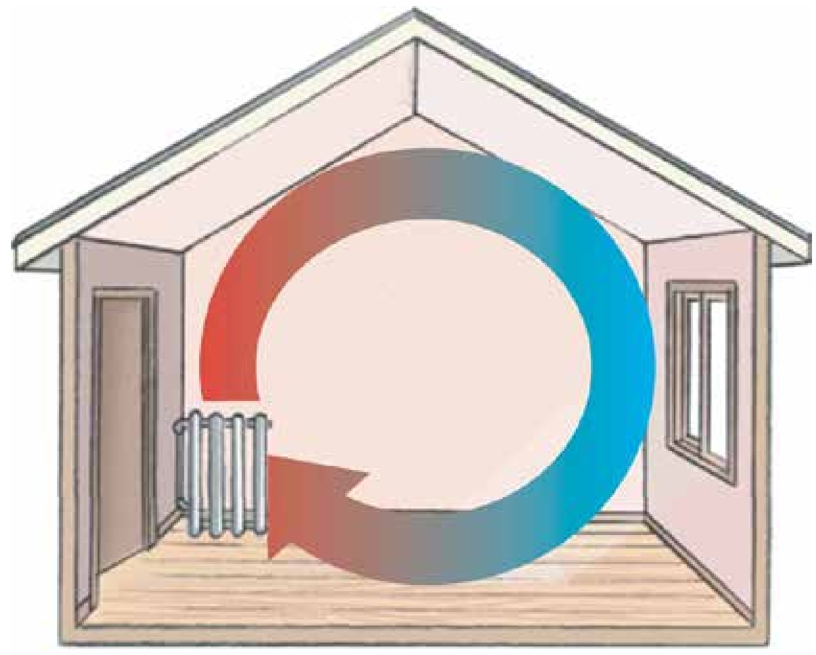
- Energy transfer by the **bulk movement** of a substance is called convection.

- **Natural convection**
  - When the movement results from differences in density.
- **Forced convection**
  - When the movement is forced by a fan or a pump.

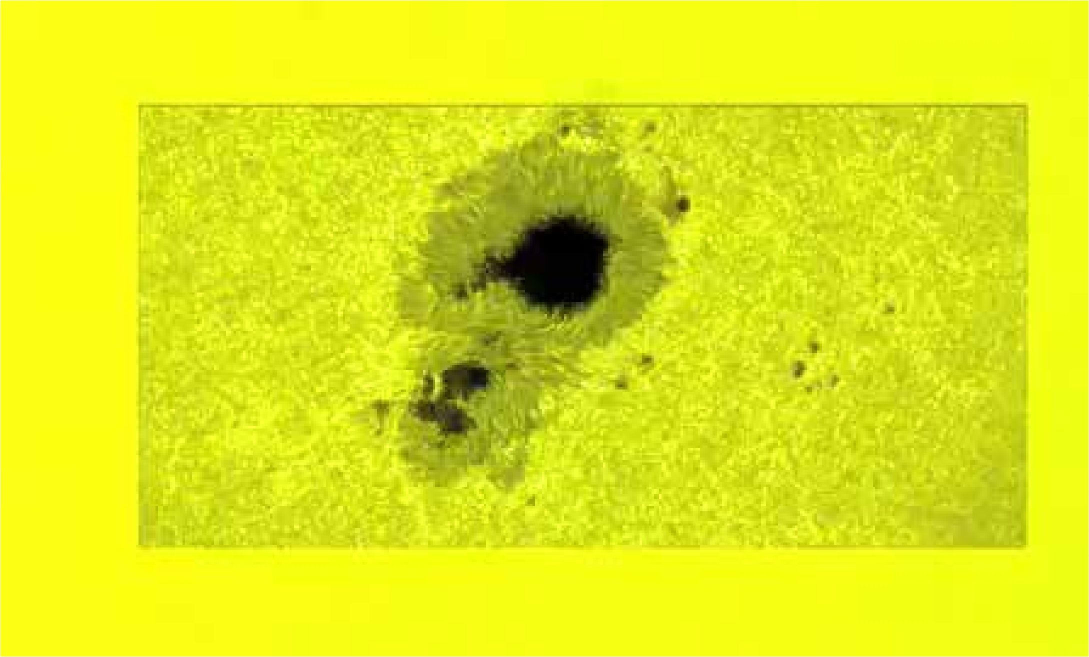


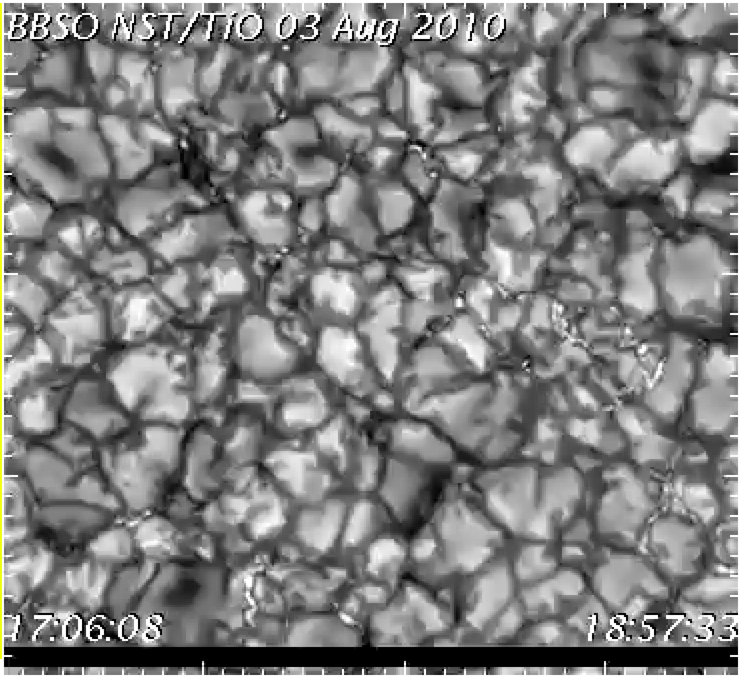
Convection example

- Air directly above the radiator is warmed and expands
- The density of the air decreases, and it rises
- A continuous air current is established



Convection on the Sun





- Main transfer of energy through outer layers of sun.
- Bulk movement of plasma: hot in centre (brighter, rising) and cooler (darker, falling) at edges.

Heat transfer>Radiation...

- **All objects** with a nonzero temperature emit energy continuously in the form of electromagnetic waves.
  - This is a consequence of the thermal motion of the constituent charged particles (dipole radiation).
  - Energy transfer in this manner does not require physical contact at all.

- In fact you can even transfer energy this way across a vacuum (e.g., sunlight).

Heat transfer>Rate of Radiation

- All objects radiate energy

- **Stefan-Boltzmann law**: The energy emitted per unit time (or power) by an object with temperature *T* is

$$P_{\text{rad}} = \sigma A e T^4$$

Joseph Stefan (1835–1893)

Ludwig Boltzmann (1844–1906)

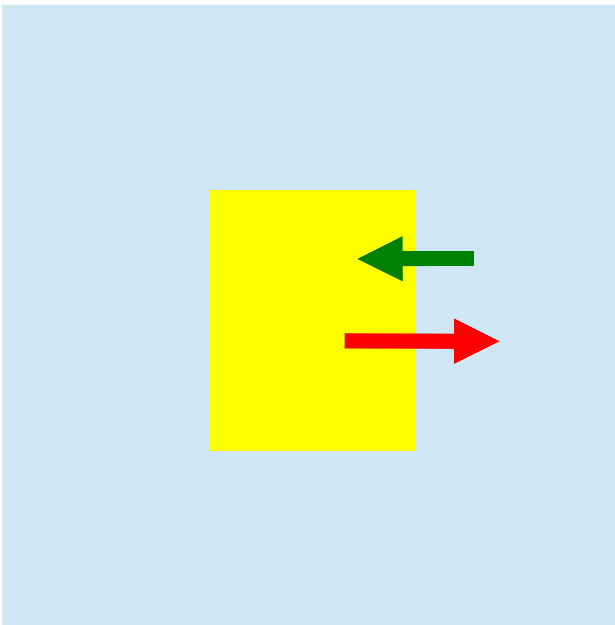
  - P_{rad} = power in Watts
  - σ = Stefan's constant = 5.6696 × 10^{-8} W m^{-2} K^{-4}
  - *A* = surface area of object
  - *e* = emissivity of the object (a number between 0 and 1)
  - T = temperature in K

Heat transfer>Radiation>Emissivity...

- The emissivity e is like an efficiency factor.
- An object with $e = 1$ is called a **black body**.
  - At any wavelength, a blackbody emits as much or more energy than any other body at the same temperature
  - It absorbs all electromagnetic radiation incident on it.\
  - Ideal emitter & ideal absorber
- A object with $e = 0$ is called a **white body**.
  - It emits no radiation and reflects all radiation.
  - Ideal reflector

Heat transfer>Radiation>Emissivity...

- **Kirchhoff's law**: a good absorber is a good emitter.



- Rate of energy **absorbed** from the environment by the body:

$$P_{\text{abs}} = \sigma A e T_{env}^{4}$$

Same e
(of the body)

- Rate of energy **emitted** by body:

$$P_{\text{rad}} = \sigma A e T_{body}^{4}$$

- **Net** energy exchange rate: $P_{\text{net}} = \sigma A e \left(T_{\text{body}}^{4} - T_{\text{env}}^{4} \right)$

Question

A sphere of radius 0.500 m, temperature 27.0^{o}C, and emissivity 0.850 is located in an environment of temperature 77.0 ^{o}C. At what rate does the sphere

a) emit and
b) absorb thermal radiation?
c) What is the sphere's net rate of energy exchange?

Hint: What is doing the emitting? Use that temperature for T.

Question

Suppose that you intercept 5.0×10^{-3} of the energy radiated by a hot sphere of radius 0.020 m, and emissivity of 0.80, and surface temperature 500 K. How much energy do you intercept in 2.0 min?