Today:

- Heat Transfer Mechanisms:
  - More on Conduction
  - Convection
  - Thermal radiation
A copper pot containing boiling water sits on a hot stove element. The temperature of the water is 100 °C. The bottom of the pot has an area of 0.04 m² and a thickness of $4 \times 10^{-3}$ m. $k$ for copper is 400 W/(m K).

If the stove element outputs 4000 W of heat to the pot, what is the temperature difference $\Delta T$ across the copper bottom of the pot?

\[
\Delta T = ?
\]

A. 0.1 °C  
B. 1 °C  
C. 10 °C  
D. 100 °C  
E. 400 °C

\[
\begin{align*}
\Delta T &= \frac{PL}{kA} \\
&= \frac{4000 \text{ W} \cdot 4 \times 10^{-3} \text{ m}}{400 \text{ W/(m K)} \cdot 0.04 \text{ m}^2} \\
&= 10 \text{ K}
\end{align*}
\]
\[ R \text{-value of material} = \frac{L}{K} \]

- measure of thermal resistance to heat flow
- used to specify building materials:

\[ P = JK \frac{A}{L} (T_H - T_c) = \frac{A}{R\text{-value}} \Delta T \]

small \( K \)  

large \( L \)  

\( \rightarrow \) large \( R\text{-value} \)  

\( \rightarrow \) small \( P \) for given \( \Delta T \)  

\( \rightarrow \) good
Double pane glass window: $R = 1.6 \text{ W/F/ft}^2$

Single pane glass window: $R = 0.9 \text{ W/F/ft}^2$

Wood panels, such as sheathing: $R = 2.5 \text{ W/F/ft}^2/\text{in}$

Fiberglass: $R = 2.2 \text{ to } 4 \text{ W/F/ft}^2/\text{in}$

Poured Concrete: $R = 0.08 \text{ W/inch/F/ft}^2$

Spray foam: $R = 4 \text{ to } 7 \text{ W/F/ft}^2/\text{in}$
Heat Conduction in Series and Parallel:
(similar to springs)

- **Series:**
  \[ P_1 = P_2 = P \]
  \[ \Delta T_{\text{total}} = \Delta T_1 + \Delta T_2 = T_H - T_c \]

- **Parallel:**
  \[ \Delta T_1 = \Delta T_2 = \Delta T = T_H - T_c \]
  \[ P_{\text{total}} = P_1 + P_2 \]
2 Convection:

- heat transport by physical motion of warm fluid (gas/liquid) to a colder region
- for liquids and gases often much more effective than conduction
- Usually driven by buoyancy (on earth)
  - Density differences between warmer and cooler fluids in gravity causes fluid motion
  - Hot fluids rise, cold fluids sink
**Example: Heat transfer from warm wall**

- **Heat transfer mechanism:**
  - Conduction only (no convection)

- **Temperature profile:**
  - Initial temperature $T_H$
  - Cool down and warming up
  - Fast drop in temperature near the wall (boundary layer)

**Conduction + convection:**

- "Convection rolls"
- Large temperature gradient $\frac{dT}{dx}$
- Heat flow from wall increased by convection
Heat Transfer by Convection
Diagram of a house heating system:

- Radiator
- Furnace
- Hot water
- Cool
candle flame on Earth

B

candle flame in microgravity
Gas convection between two horizontal glass plates, with heating from below
3. Radiation:

All objects at finite temperature $T$ emit energy in the form of electromagnetic waves. $\Rightarrow$ radiate (emit) power

... radio waves ... infrared ... visible light ... x-rays

Increasing frequency $f$ decreasing wavelength $\lambda$
- Emitted wavelengths, \(\lambda\) and \(\lambda_{\text{peak}}\) depend on object's temperature \(T\):
  - You emit radio waves at IR
  - Integrate to get total power emitted by object
    \(\Rightarrow\) area under curve
    \(\Rightarrow\) goes up as temperature increases

\[ \lambda_{\text{peak}} \propto \frac{1}{T} \] wave length at which max. intensity is emitted

\( T \) in Kelvin!
Apparent Color of a “black body” vs. temperature
• Power radiated:

\[ P_{\text{radiated by}} = \varepsilon A_{\text{obj}} T_{\text{obj}}^4 \]

Object to environment

Surface area of object

\[ T_{\text{obj}} \quad \text{Kelvin} \]

• At same time, object is absorbing power from the environment:

\[ P_{\text{absorbed by}} = \varepsilon A_{\text{obj}} T_{\text{env}}^4 \]

Object from environment

\[ T_{\text{env}} \quad \text{Kelvin} \]
\[ P_{\text{net}} = \text{radiated} = P_{\text{rad}} - P_{\text{abs}} = -\frac{dQ_{\text{obj}}}{dt} = \left( \text{rate at which heat is removed from object} \right) \]

\[ P_{\text{net}} = \sigma \varepsilon A_{\text{obj}} \left( T_{\text{obj}}^4 - T_{\text{env}}^4 \right) \]

\[ \sigma = \text{Stefan-Boltzmann constant} \]
\[ = 5.67 \times 10^{-8} \, \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4} \]

\[ \varepsilon = \text{emissivity} \]
\[ - \text{property of surface} \]
\[ - \varepsilon : 0 \rightarrow 1 \]
\[ \text{[dimensionless]} \]

\[ \varepsilon = 0 \quad \text{"perfect reflector"} \]
\[ \varepsilon = 1 \quad \text{"perfect absorber"} \]
\[ \varepsilon = \text{black body} \]
An object with a temperature $T_o$ (in K) is placed in the middle of a large container whose walls are at $T_{w,i} = 0$ K.

If you raise the temperature of the walls to $T_w = T_o/2$, by what multiplicative factor does the net power that the object radiates to its environment change?

\[
\begin{align*}
T_{w,i} &= 0 \text{ K} \implies P_{\text{net},i} = ? \\
T_{w,f} &= T_o/2 \implies \frac{P_{\text{net},f}}{P_{\text{net},i}} = ? \\
\end{align*}
\]

\[
P_{\text{net},i} = \sigma \varepsilon A_{\text{obj}} (T_o^4 - 0 K^4)
\]

\[
P_{\text{net},f} = \sigma \varepsilon A_{\text{obj}} (T_o^4 - T_w^4)
\]

\[
= \sigma \varepsilon A_{\text{obj}} (T_o^4 - (T_o/2)^4)
\]

\[
= \sigma \varepsilon A_{\text{obj}} (T_o^4 - T_o^4/16)
\]

\[
= \sigma \varepsilon A_{\text{obj}} \frac{15}{16} T_o^4 = \frac{15}{16} P_{\text{net},i}
\]

- A. 1/16
- B. 1/4
- C. 1/2
- D. 15/16
- E. 1

The multiplicative factor is $15/16$. Therefore, the correct answer is D. 15/16.
Radiation Examples

Dewar Flasks
(e.g. Thermos)
Why do you have to scrape your windshield even when the air temperature doesn't go below 0 °C?

At night the car cools by radiation into space.

Clouds/ water vapor absorb radiation and radiate it back to Earth, reducing the net cooling rate.

Water vapor content of the air at 0 °C (32 °F) is ~7 times smaller than at 30 °C (86 F)

Effective temperature of a clear, dry night sky ~ - 40 °C.
In cool weather, car sees -40 °C of sky and radiates its heat energy, cooling below the temperature of the surrounding atmosphere.

Water vapor in air condenses and freezes on cool car.

**Solution: Use a carport**
Thermography

- Imaging surface temperature of an object using the **infrared radiation** it emits.
Medical Thermography
Person Before and After Low-Impact Aerobics:
Pregnant woman: