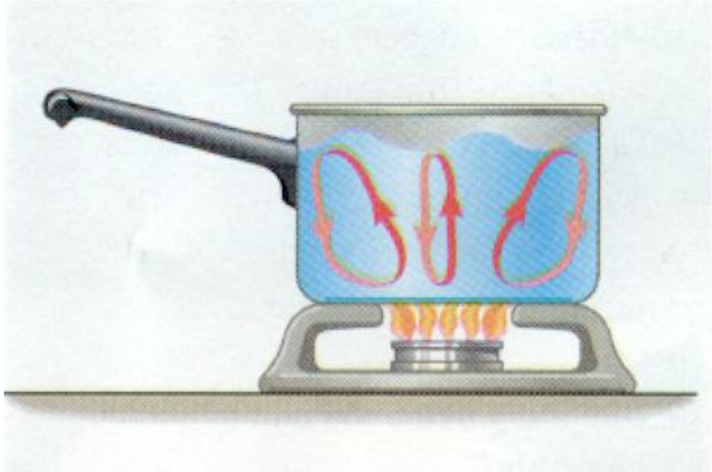
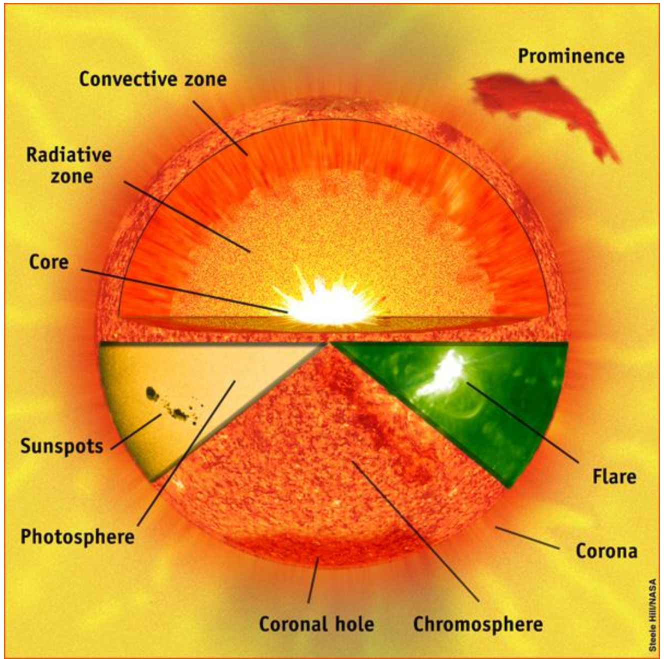
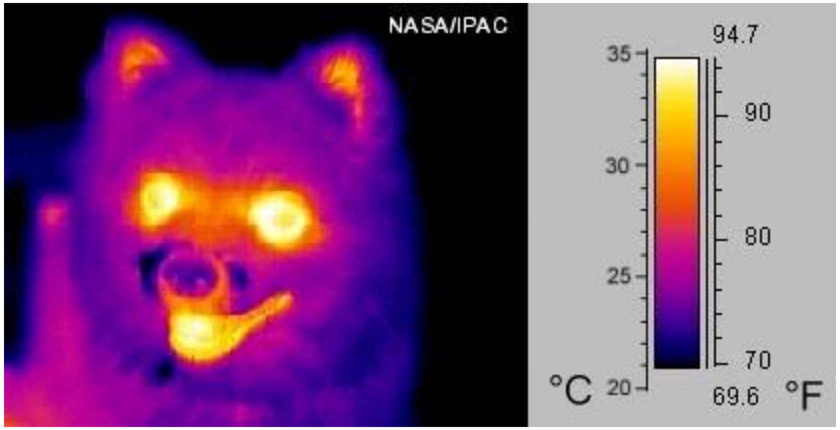
Today:

- **Heat Transfer Mechanisms:**
  - More on Conduction
  - Convection
  - Thermal radiation

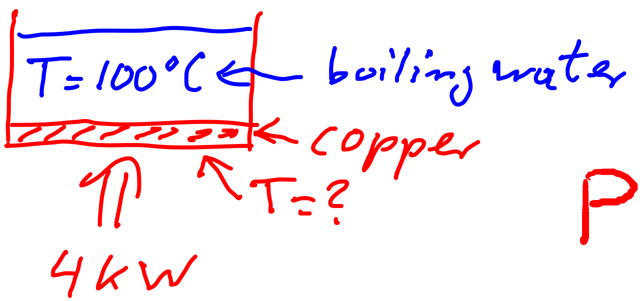






A copper pot containing boiling water sits on a hot stove element. The temperature of the water is 100 °C. The bottom of the pot has an area of 0.04 m^2 and a thickness of 4 x 10^{-3} m. *k* for copper is 400 W/(m K).

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



$$P = \frac{dQ}{dt} = \kappa \frac{A}{L} \Delta T$$

$$\Rightarrow \Delta T = \frac{PL}{\kappa A} = \frac{4000\,W \cdot 4 \cdot 10^{-3}\,m}{400\,\frac{W}{mK}\, 0.04\,m^2}$$

$$= 1°K$$

ΔT = ?

A. 0.1 °C

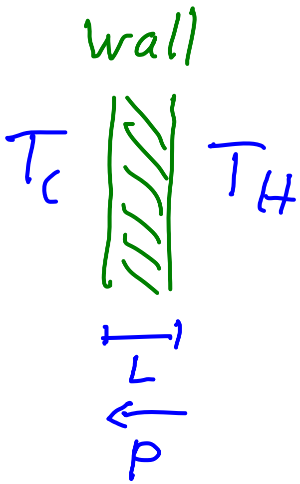
B. 1 °C

C. 10 °C

D. 100 °C

E. 400 °C

→ related : R-value:



$$\text{R-value of material} \equiv \frac{L}{k}$$

L ← thickness
k ← thermal conductivity

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

$$P = k\frac{A}{L}(T_H - T_C) = \frac{A}{\text{R-value}}\Delta T$$

small k
large L → large R-value → small P for given ΔT

→ good

Poured Concrete: R=0.08 W/inch/F/sft

Single pane glass window: R = 0.9W/F/sft

Double pane glass window: R = 1.6W/F/sft

Wood panels, such as sheathing: R=2.5 W/F/sft/inch

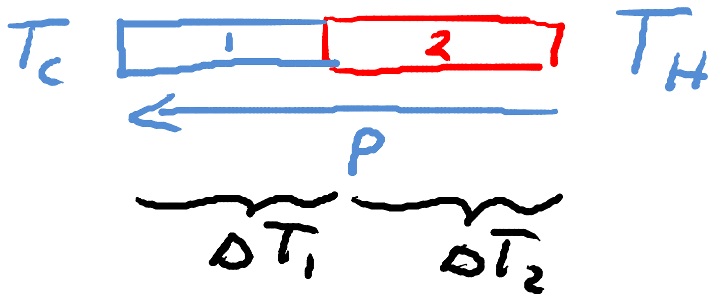
Fiberglass: R = 2.2 to 4W/F/sft / inch

Spray foam: R= 4 to 7W/F/sft / inch

→ Heat Conduction in Series and Parallel:

(similar to springs)

- **Series:**

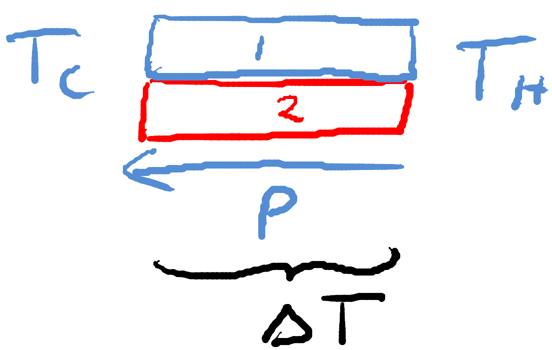


$$P_1 = P_2 = P$$

$$\Delta T_{total} = \Delta T_1 + \Delta T_2$$
$$= T_H - T_C$$

- **Parallel:**

$$\Delta T_1 = \Delta T_2 = \Delta T = T_H - T_C$$

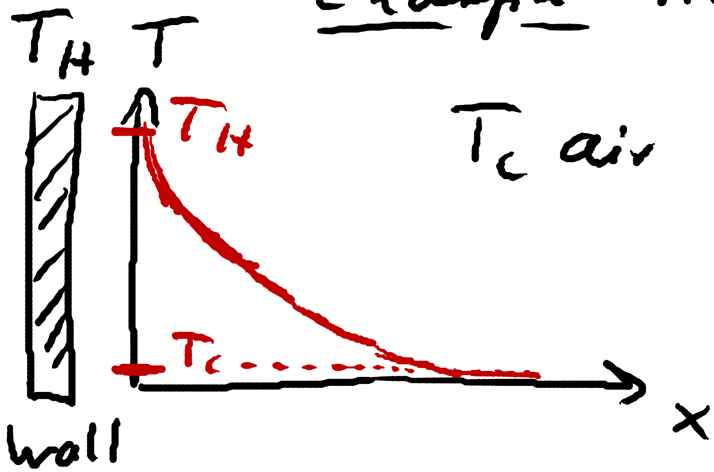


$$P_{total} = P_1 + P_2$$

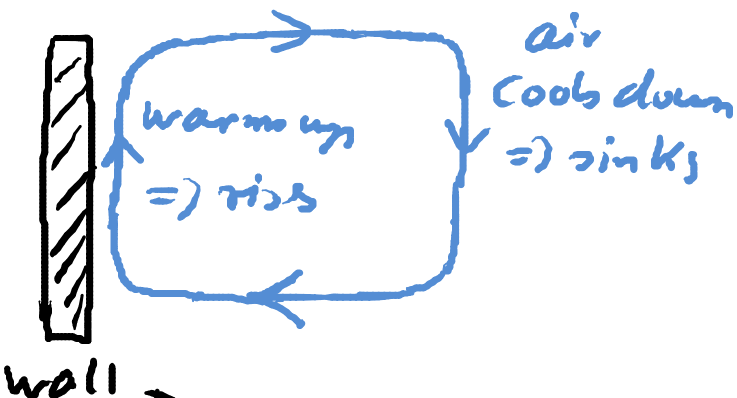
② Convection:

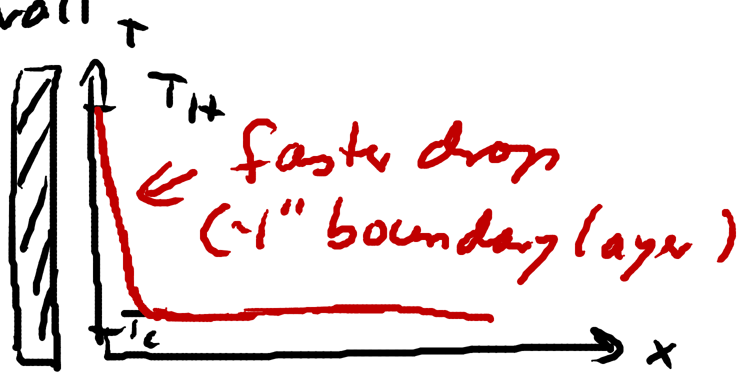
- heat transport by physical motion of warm fluid (gas/liquid) to a colder region
- for liquids and gases often much more effective than conduction
- Usually driven by buoyancy (on earth)
  → Density differences between warmer and cooler fluids in gravity causes fluid motion
  → Hot fluids rise, cold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

Example: Heat transfer from warm wall



air, conduction only (no convection)





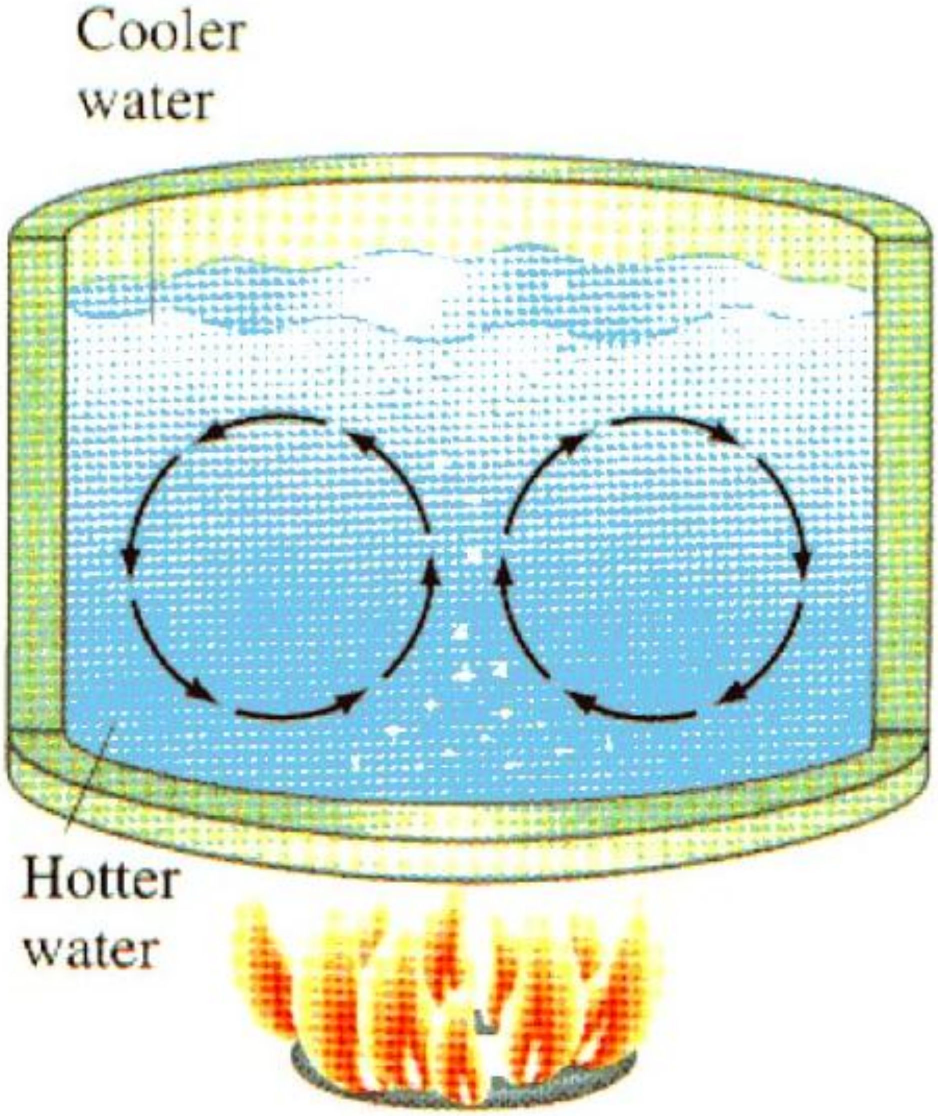
conduction + convection:

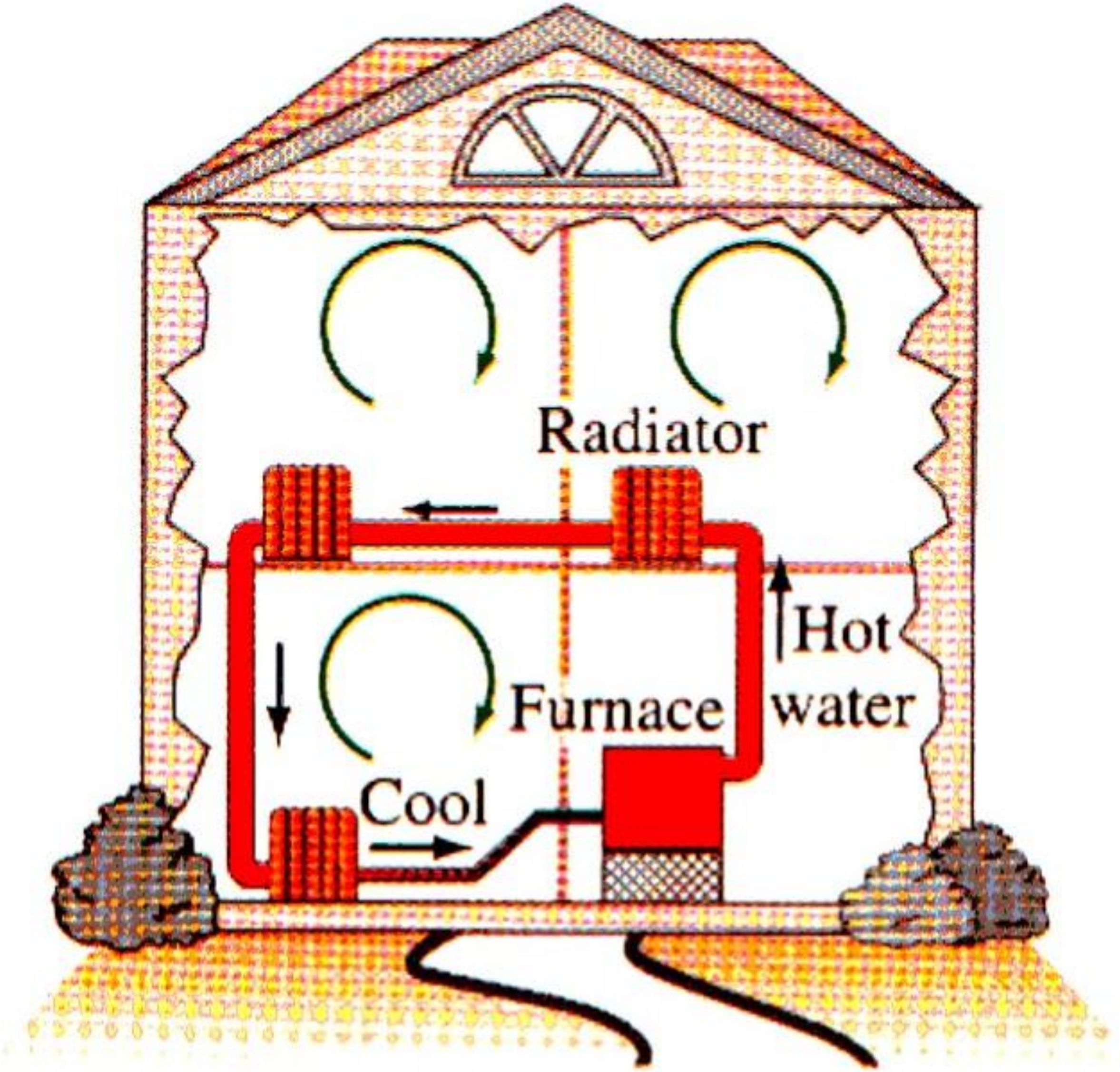
=> "convection rolls"

=> large temp. gradient $\frac{dT}{dx}$ near wall

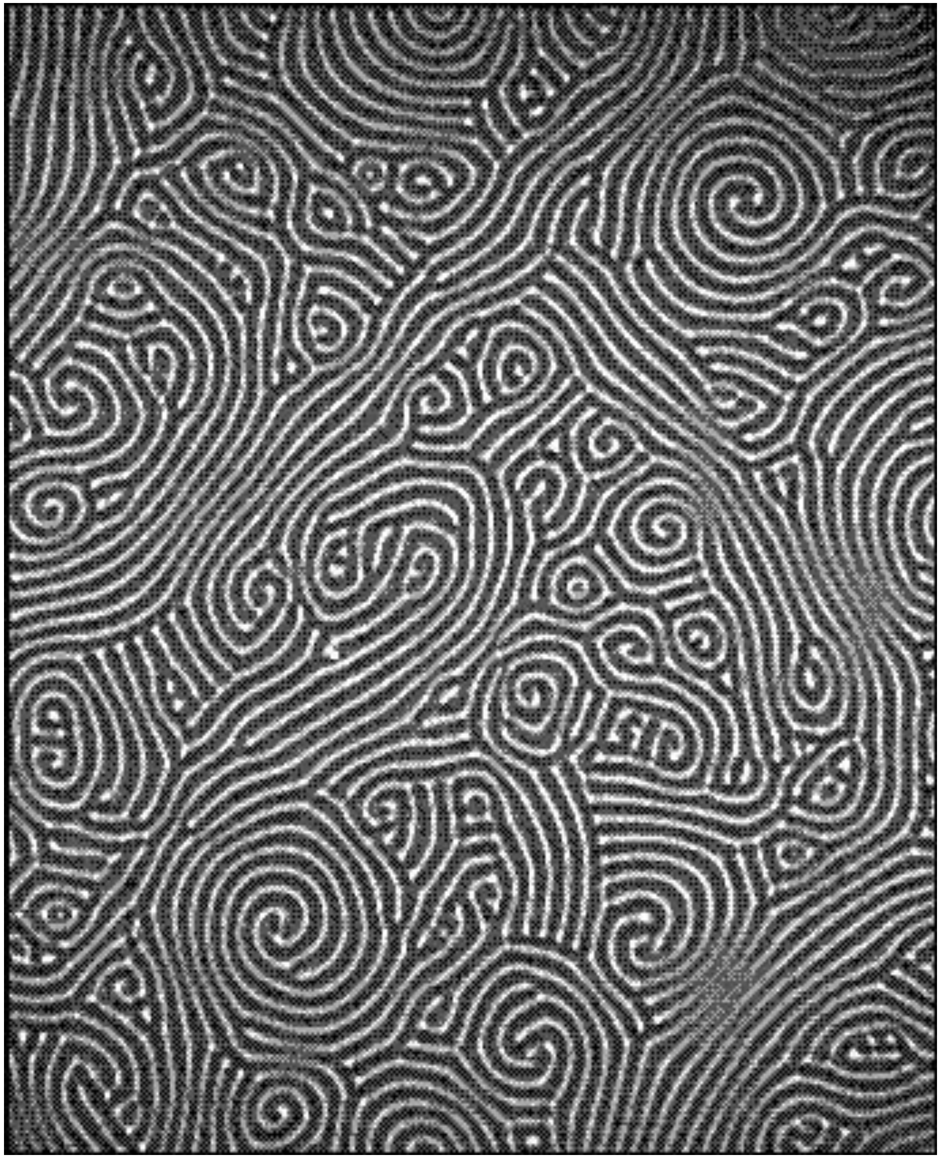
=> heat flow from wall by conduction is increased by convection

Heat Transfer by Convection




Radiator
Hot
water
Furnace
Cool


A
candle flame on Earth
B
candle flame in microgravity



Gas convection between two horizontal glass plates, with heating from below

③ Radiation:

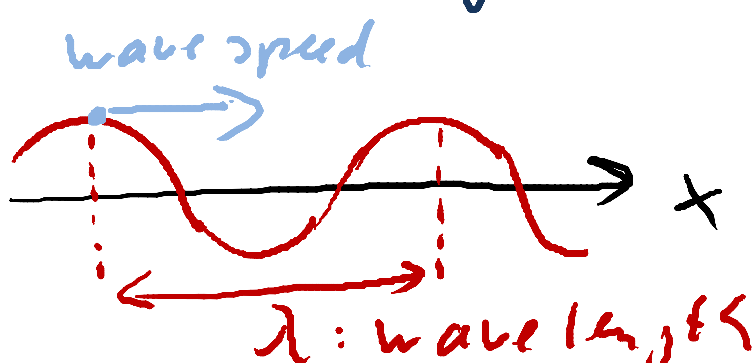
All objects at finite temperature T emit energy in the form of electromagnetic waves!

⇒ radiate (emit) power

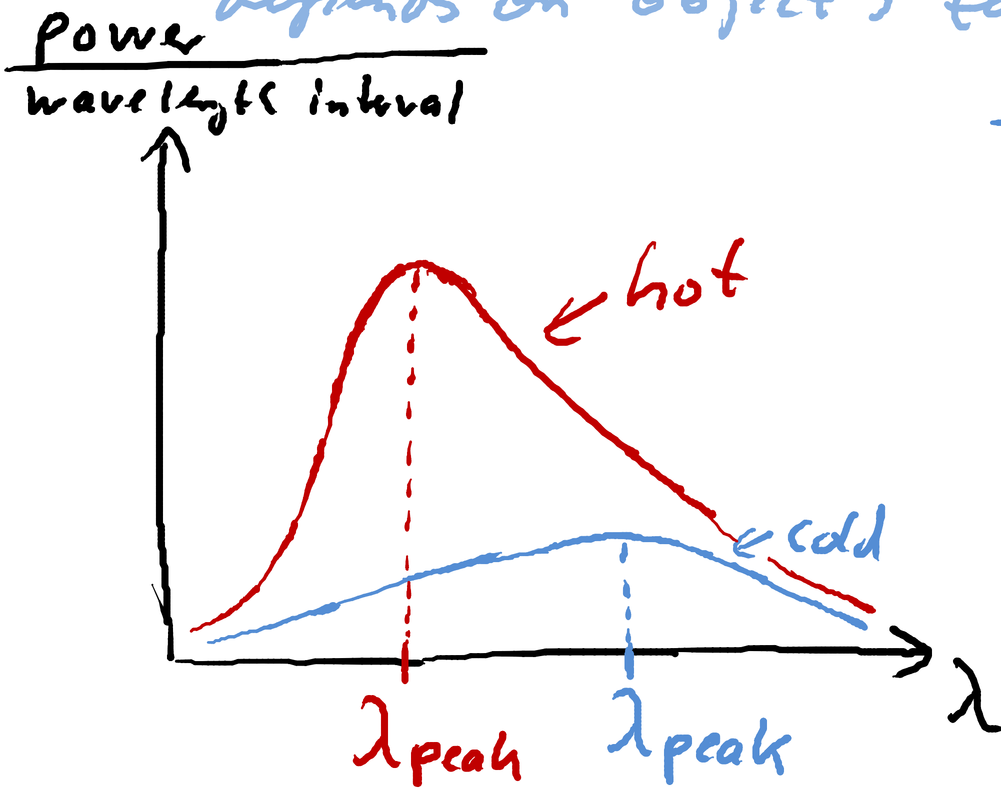
... radio waves ... infrared .... visible light .... x-rays

⟶ increasing frequency f

decreasing wavelength λ



→ Emitted wavelengths (λ's) and λ_{peak} depends on object's temperature T:

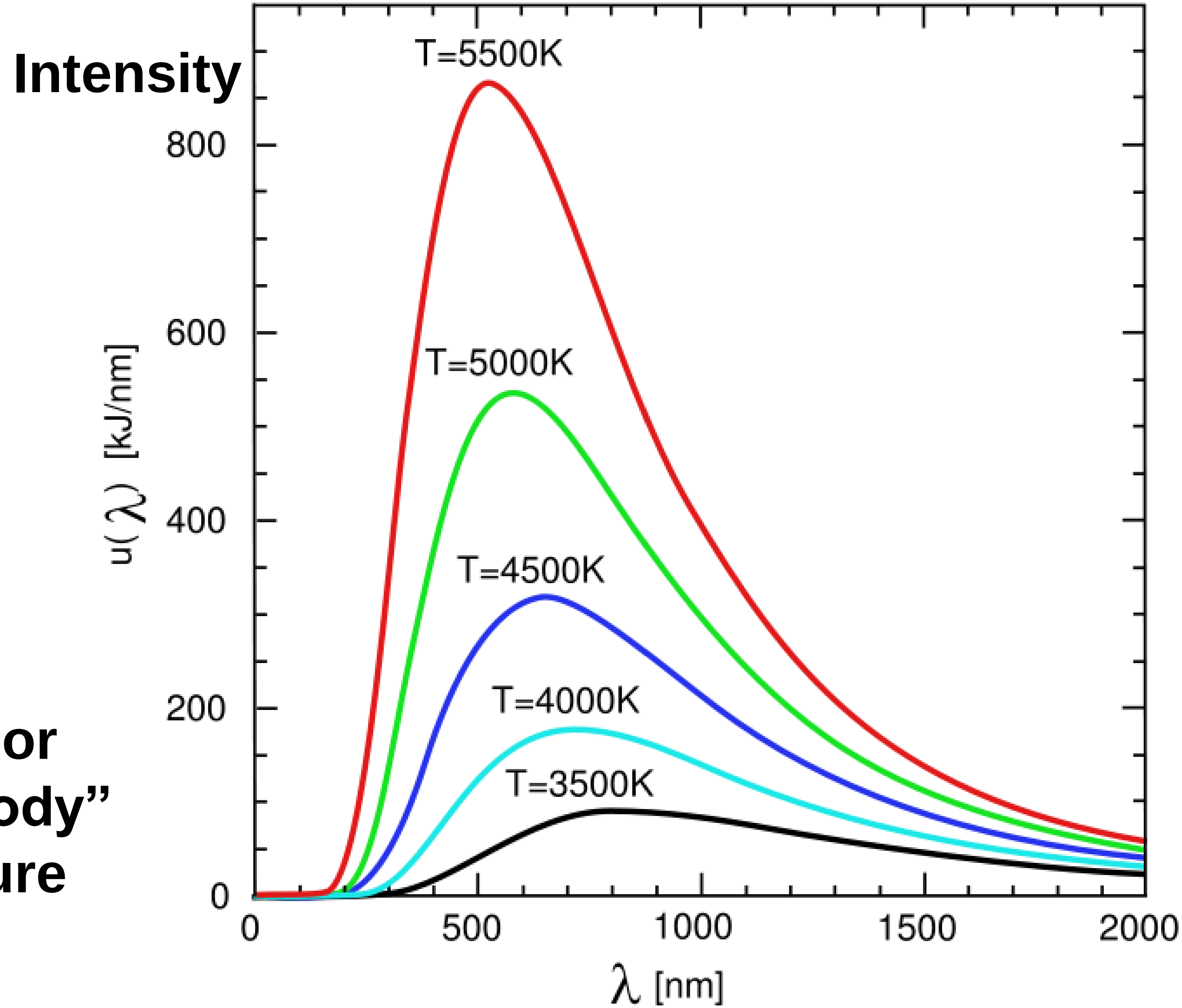


- you emit radio waves or IR
- Integrate to get total power emitted by object = "area under curve"

⇒ goes up as temperature increases

$\lambda_{peak} \propto \frac{1}{T}$ } wavelength at which max. intensity is emitted

T in Kelvin!



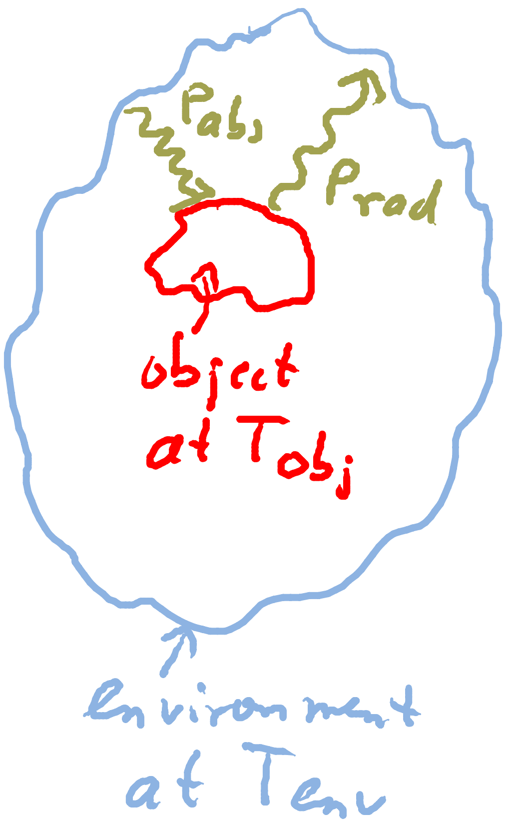
Apparent Color of a “black body” vs. temperature

- Power radiated:

$$P_{\text{radiated by object to environment}} = \sigma \, \varepsilon \, A_{obj} \, T_{obj}^4$$

A_{obj}: surface area of object

T_{obj}^4 ← ! T in Kelvin!



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

$$P_{\text{absorbed by object from environment}} = \sigma \, \varepsilon \, A_{obj} \, T_{env}^4$$

T_{env}: T in Kelvin!

$\Rightarrow$ $P_{net\ radiated} = P_{rad} - P_{abs} = -\dfrac{dQ_{obj}}{dt} =$ (rate at which heat is removed from object)

from object to environment

$$\Rightarrow P_{net} = \sigma\, \varepsilon\, A_{obj} \left(T_{obj}^4 - T_{env}^4 \right)$$

in Kelvin!

σ = Stefan-Boltzmann constant

$$= 5.67 \cdot 10^{-8} \frac{W}{m^2 K^4}$$

ε = emissivity

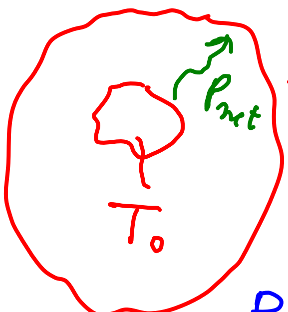
- property of surface
- ε : $0 \to 1$ [dimensionless]

$\varepsilon = 0$ "perfect reflector"

$\varepsilon = 1$ "perfect absorber" "perfect emitter" "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?



$T_{w,i} = 0K \rightarrow P_{net,i} = ?$

$T_{w,f} = T_o/2 \rightarrow \dfrac{P_{net,f}}{P_{net,i}} = ?$

$P_{net,f}/P_{net,i} = ?$

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

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

$= \sigma \varepsilon A_{obj} (T_o^4 - (\frac{T_o}{2})^4)$

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

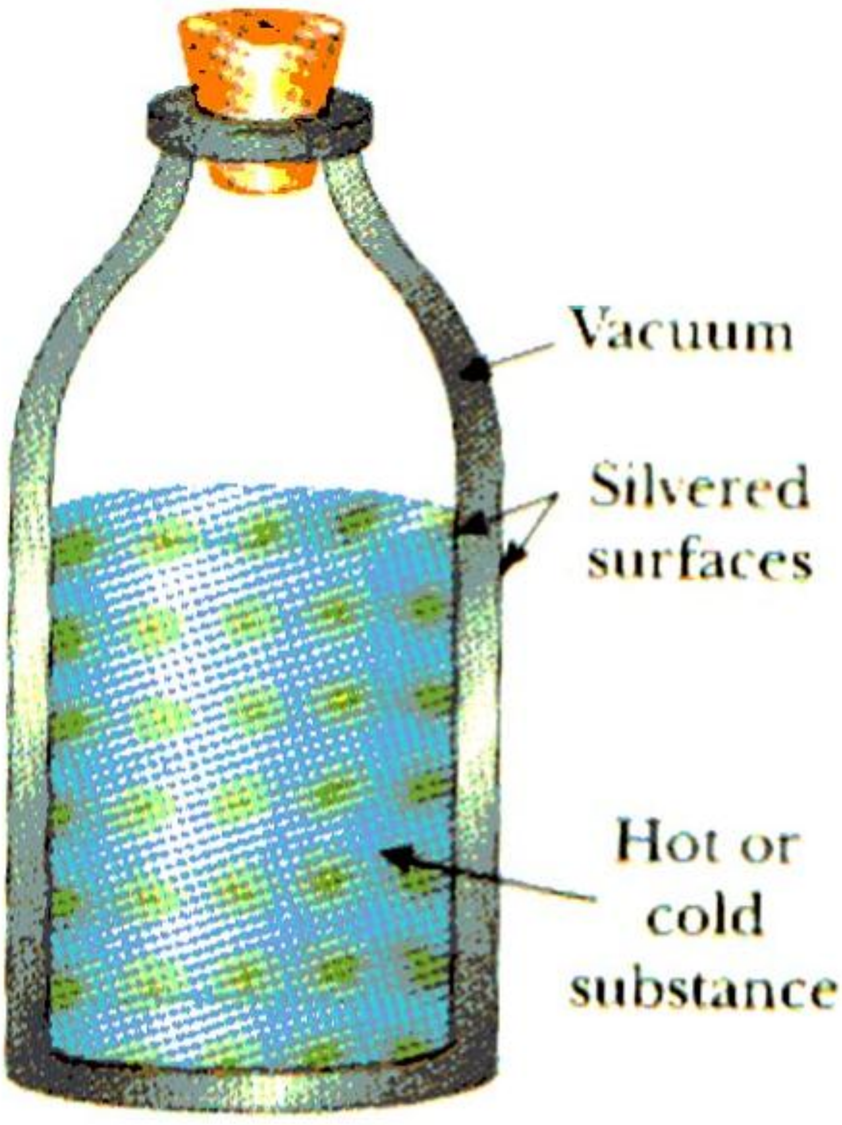
$= \sigma \varepsilon A_{obj} \frac{15}{16} T_o^4 = \frac{15}{16} P_{net,i}$

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

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.

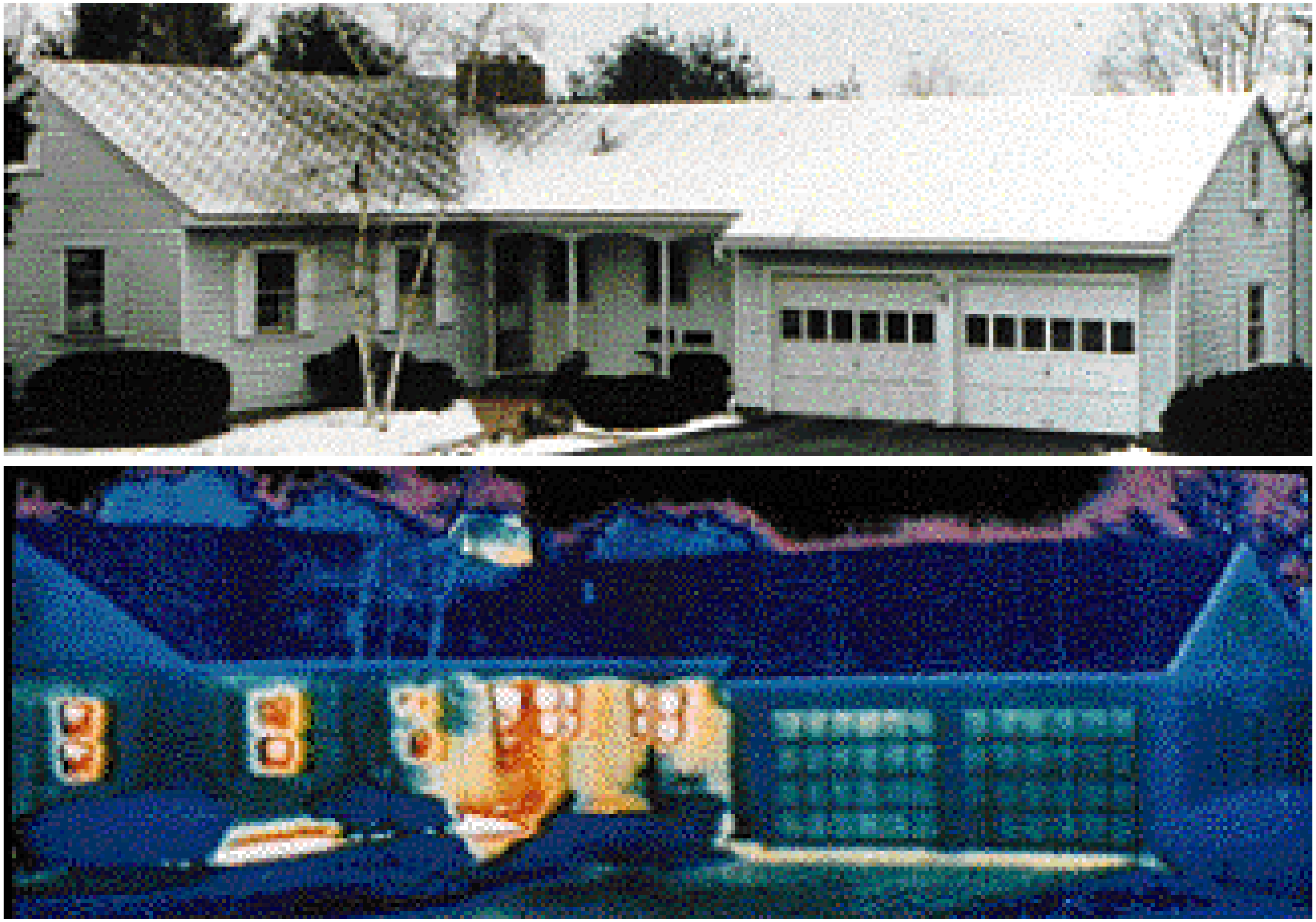
∴ In cool weather, car sees -40 °C of sky and radiates its heat energy, cooling below the temperature of the surrounding atmosphere.

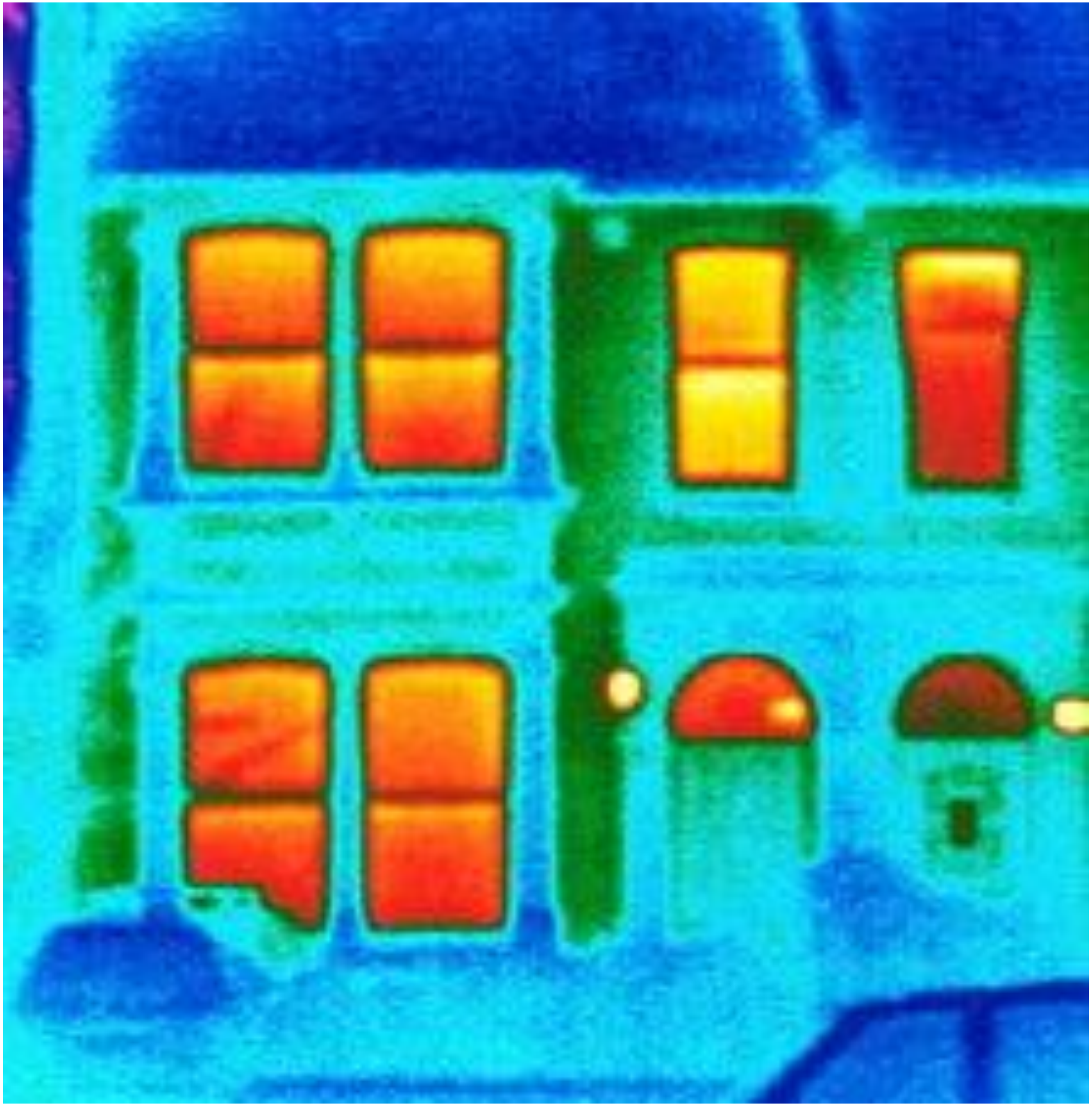
Water vapor in air condenses and freezes on cool car.

Solution: Use a carport

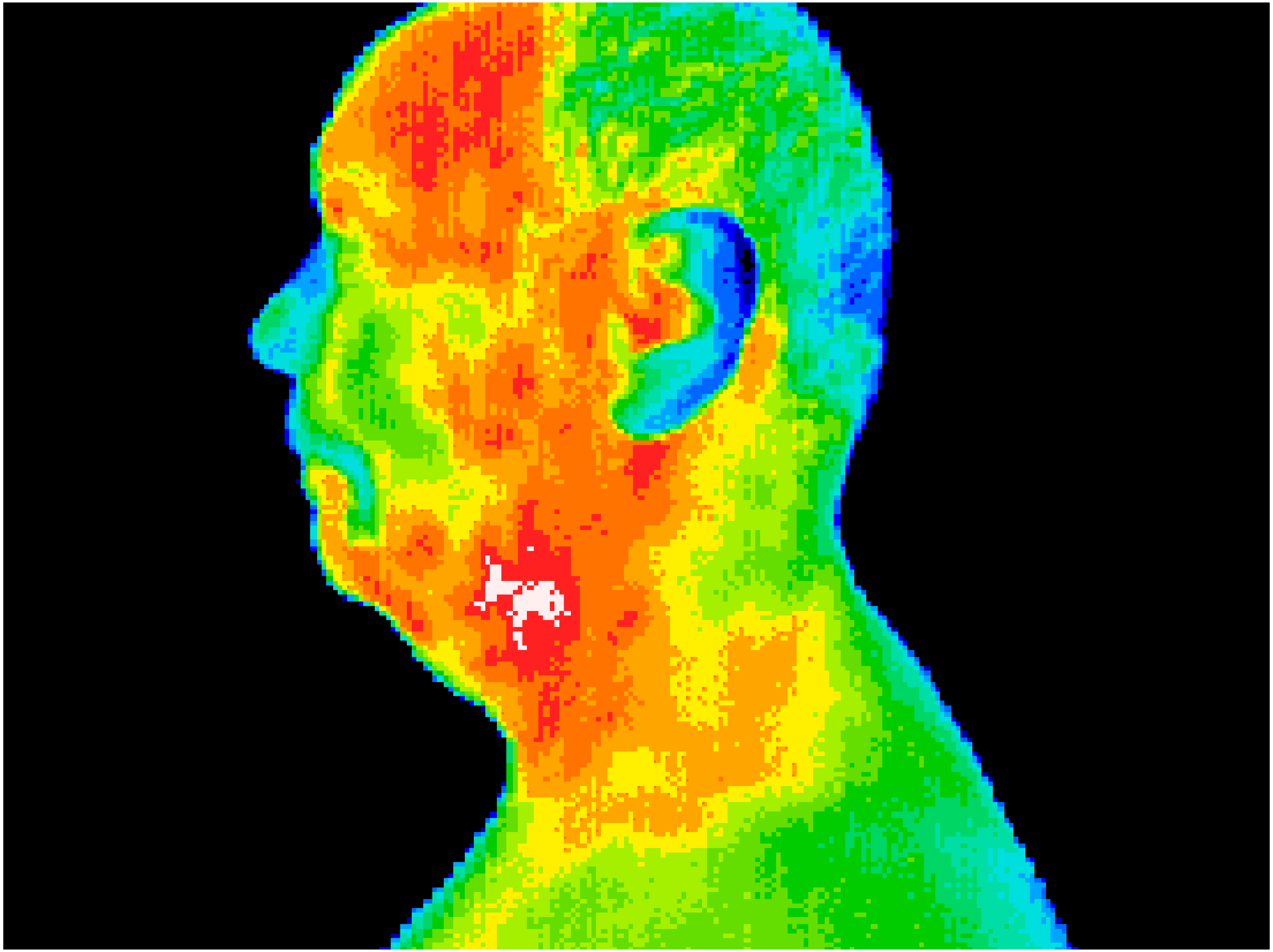
Thermography

- Imaging surface temperature of an object using the **infrared radiation** it emits.

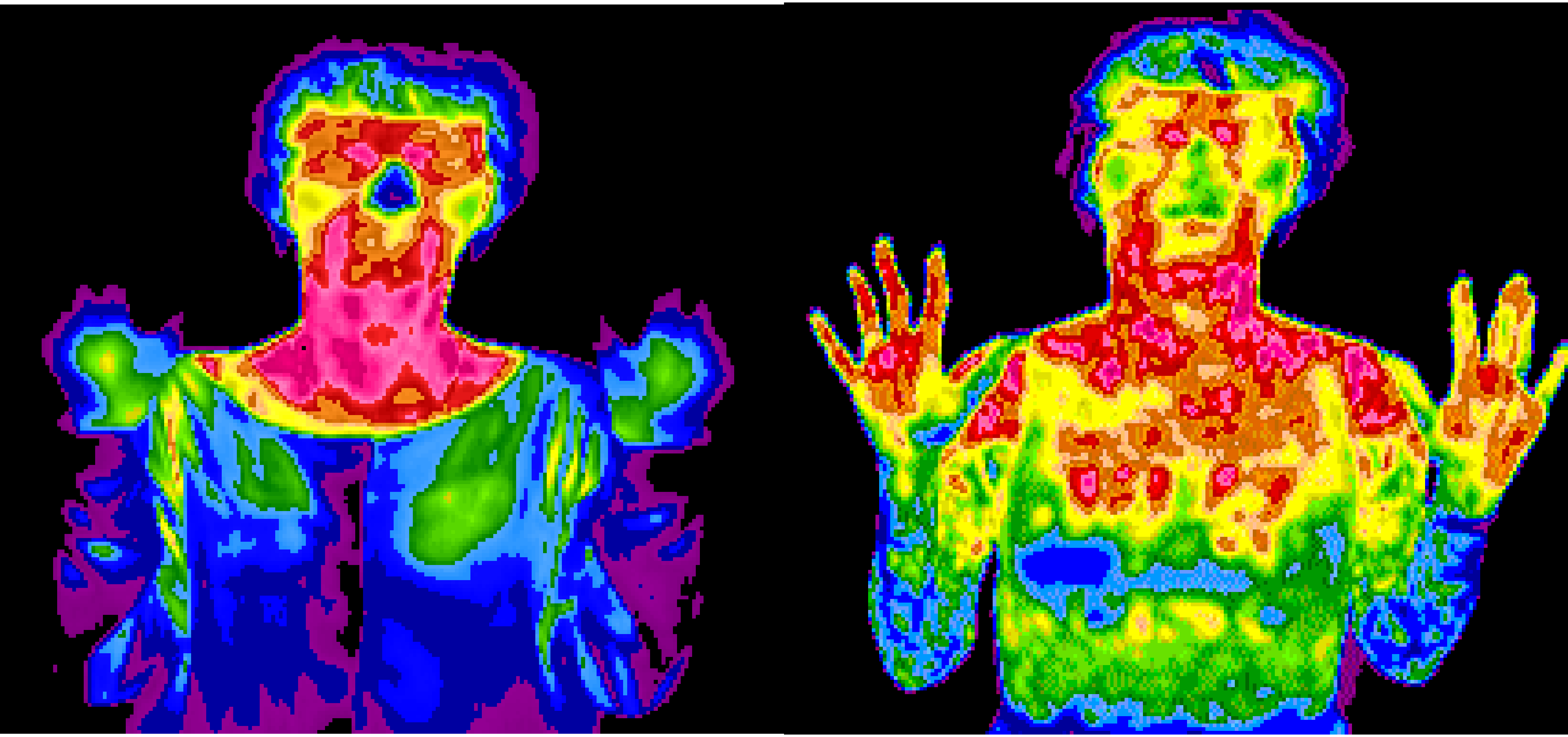




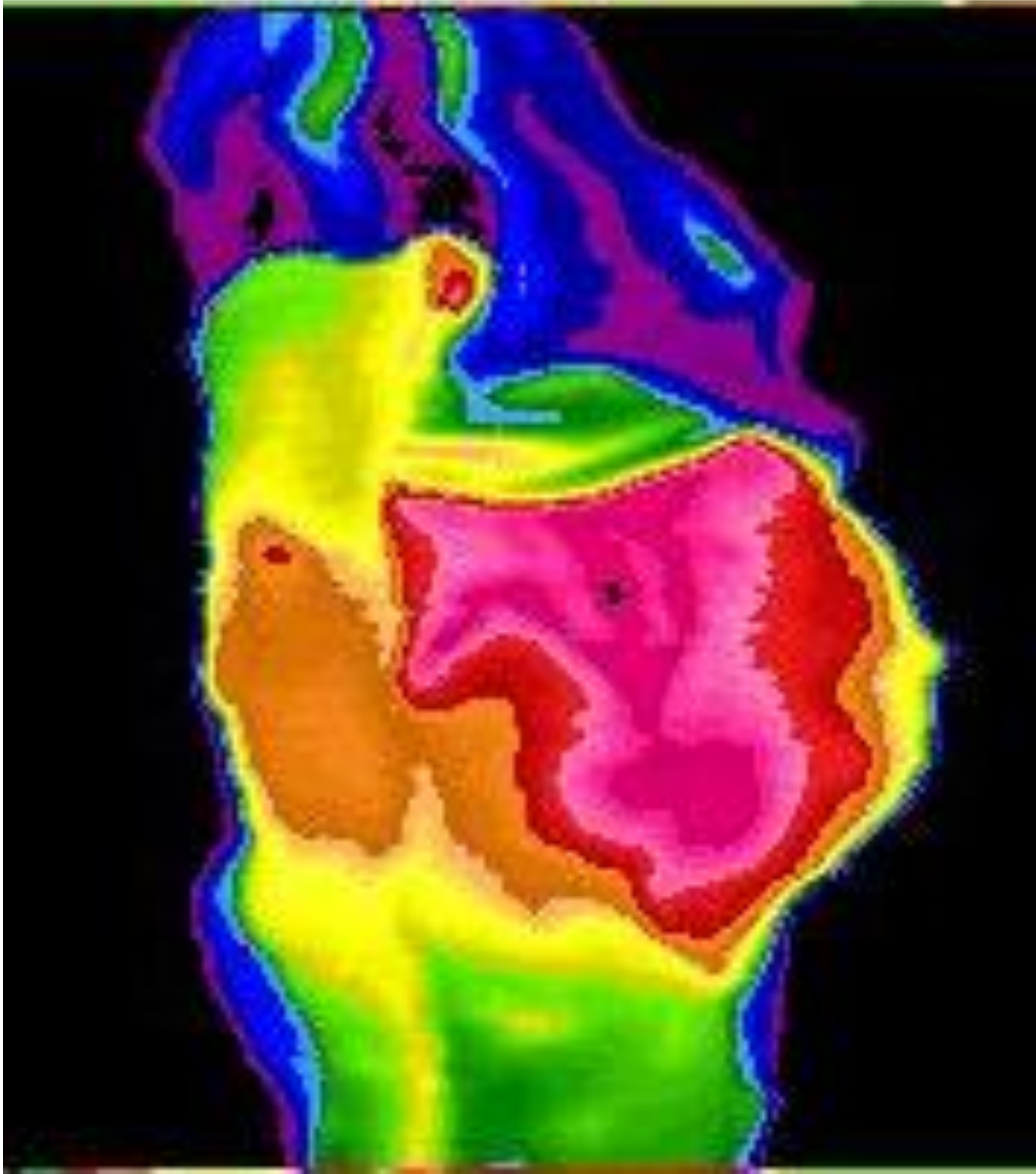
Medical Thermography



Person Before and After Low-Impact Aerobics:



Pregnant woman:



Sprained Ankle: