Lecture 4

Mechanisms of heat transfer

Pre-reading: §17.7

Review

Heat can be transferred from one object to another due to a temperature difference.

The properties of many objects change with temperature: length, volume

$$\Delta L = \alpha L_o \Delta T \qquad \Delta V = \beta V_0 \Delta T$$

When we add heat to an object, we can change

– its temperature $Q = mc\Delta T$

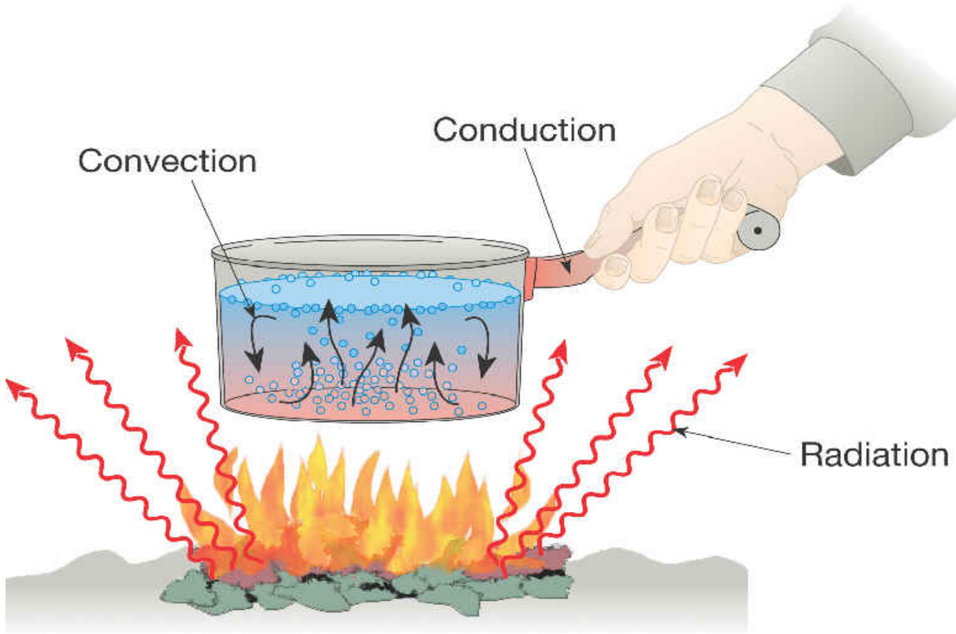
– and/or its phase $Q = \pm mL_f$

Heat transfer

We have seen how heat Q is transferred between bodies due to temperature difference ΔT.

There are three mechanisms of heat transfer:

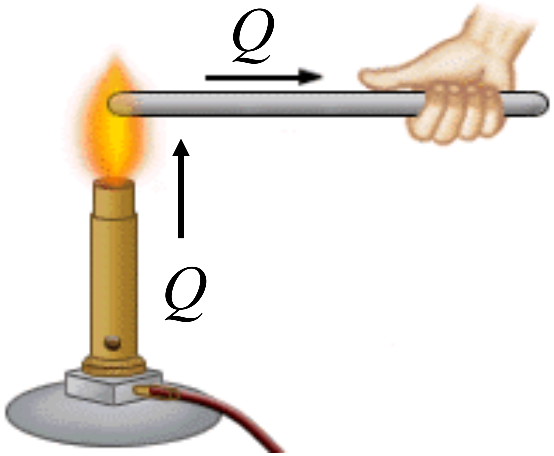
1. *conduction*: within a body or between two bodies in contact
2. *convection*: heat carried by motion of mass
3. *radiation*: heat transfer by electromagnetic radiation



Conduction

Conduction is heat transfer by means of molecular agitation within a material without any motion of the material as a whole.

Higher speed particles will collide with the slower ones, with a net transfer of energy to the slower ones.



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Conduction: Heat current

The rate of heat transfer is called *heat current* H.

Find the heat current depends on

– the temperature difference ΔT

– the cross-sectional area A

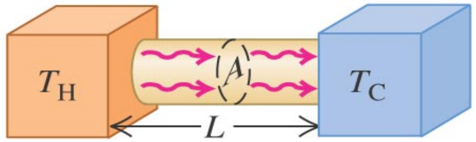
– the *inverse* of the length

$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L}$$

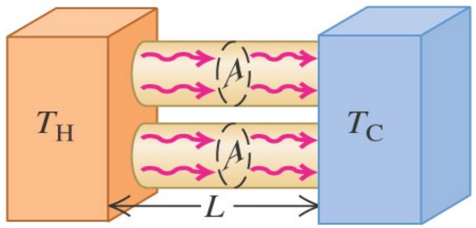
k is the *thermal conductivity*

Units: $\mathrm{W.m^{-1}K^{-1}}$

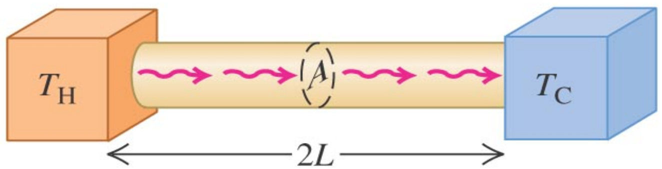
(a) Heat current H



(b) Doubling the cross-sectional area of the conductor doubles the heat current (H is proportional to A).



(c) Doubling the length of the conductor halves the heat current (H is inversely proportional to L).



Material	Thermal conductivity k ($W.m^{-1}.K^{-1}$)
diamond	2450
Cu	385
Al	205
Brick	0.2
Glass	0.8
Body fat	0.2
Water	0.6
Wood	0.2
Styrofoam	0.01
Air	0.024

Thermal conductivity k is a property of the material.

High k: conductors
low k: insulators

Question

Why do droplets of water dance over the very hot pan ?

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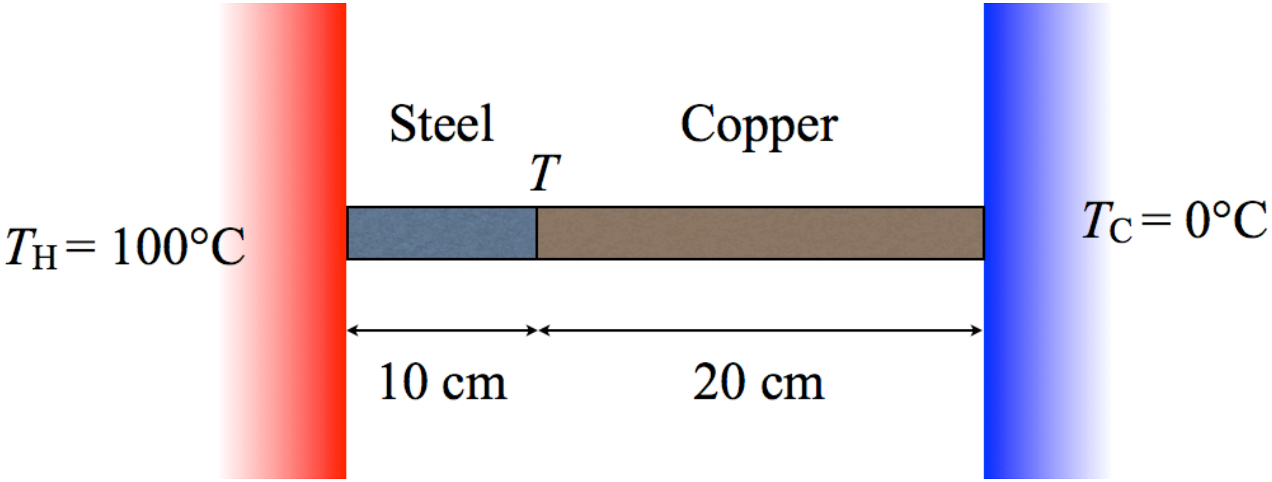
Heat current

Consider two materials in contact, with heat flowing through them.



In steady state, the same heat has to pass through both materials in succession, so the heat flow must be the same in both materials.

Take $k_{steel} = 50.2$ W.m^{-1}K^{-1}, $k_{copper} = 385.0$ W.m^{-1}K^{-1}

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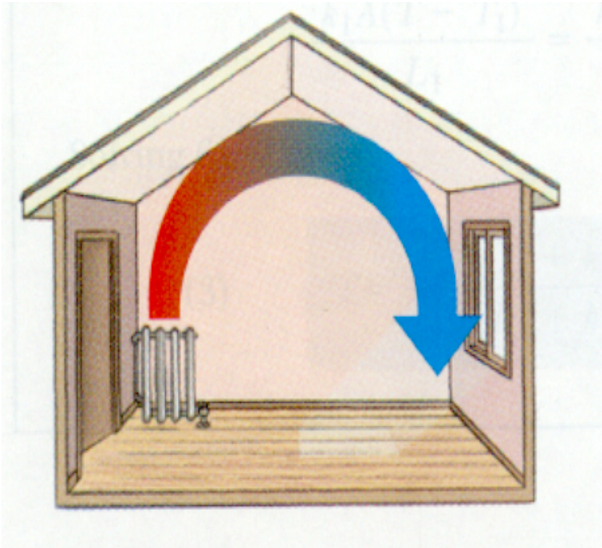
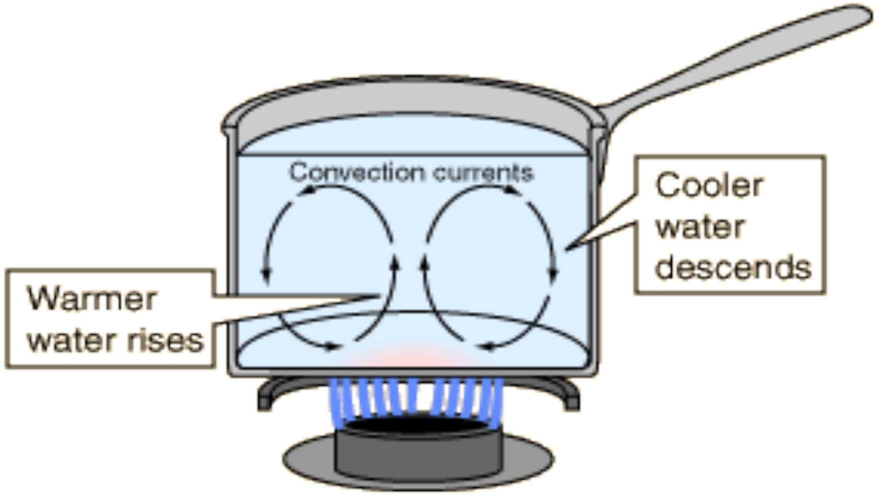
Question

Why does it feel colder to sit on a metal bench than a wooden one?

Convection

Convection is heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it.





No simple equation to describe it.

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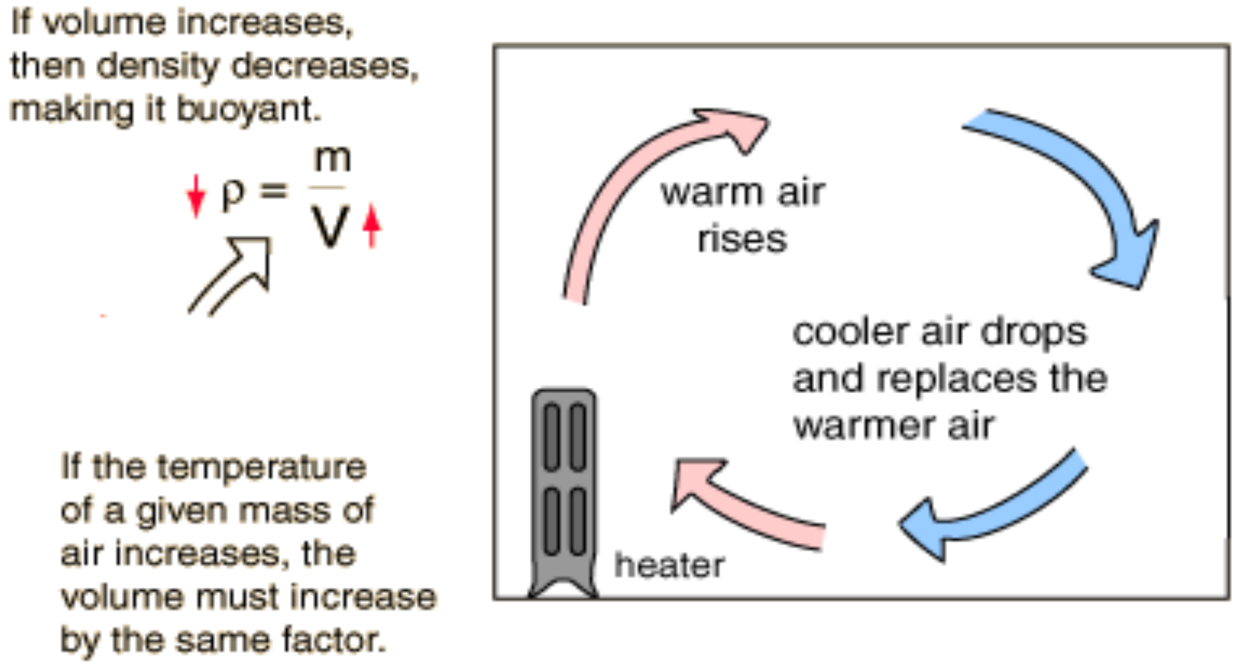
Convection: Heat current



Typically find heat current due to convection is

$$\frac{dQ}{dt} \approx hA(T_2 - T_1)^a$$

a = 1 or 5/4 depending on context

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Question

Why don't ducks get cold feet?

Radiation

Radiation is heat transfer by electromagnetic waves such as visible light, UV and infrared radiation.

Anything above absolute zero radiates heat.

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Radiation: Heat current

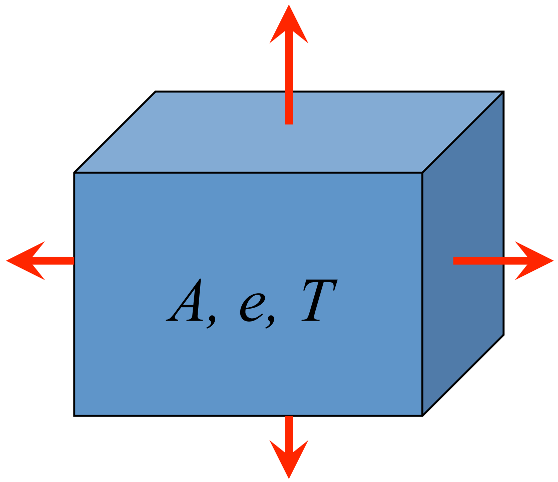
Heat current due to radiation depends on the area of the surface and the fourth power of the temperature:

$$H_{rad} = \frac{dQ_{rad}}{dT} = Ae\sigma T^4$$

e is the *emissivity* of the surface ($0 < e < 1$)

σ is called the *Stefan-Boltzmann constant*:

$\sigma = 5.67 \times 10^{-8}$ W.m^{-2}.K^{-4}



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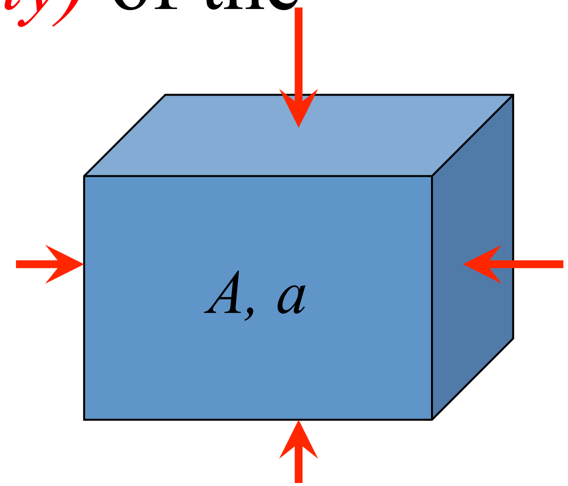
Heat emitters are heat absorbers

Power absorbed by the surface of an object

$$H_{abs} = \frac{dQ_{abs}}{dt} = Aa\sigma T_s^{\ 4}$$

a is the absorption coefficient (*absorptivity)* of the surface ($0 < a < 1$)

Since in equilibrium the heat flow must be 0, $a = e$



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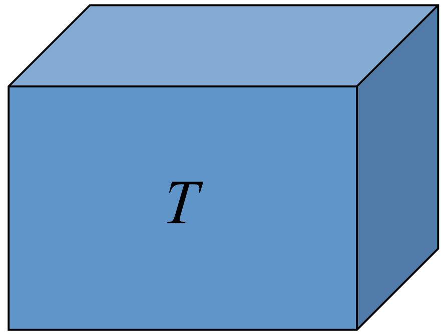
Net radiation

So an object at temperature T is radiating, but it can also absorb radiation from its surroundings (at temperature T_s). Hence the *net* heat flow is

$$H_{net} = Ae\sigma T^4 - Ae\sigma T_s^4 = Ae\sigma(T^4 - T_s^4)$$

Once again, the heat current depends on the temperature *difference* between two bodies.



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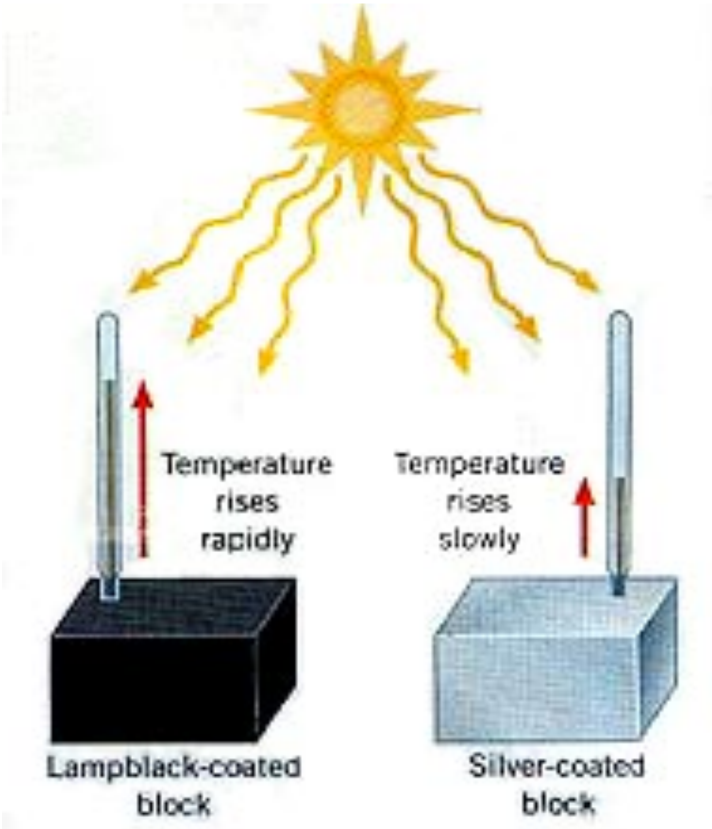
Emissivity/absorptivity, *e*

Black surface ($e \sim 1$)
– good emitter / absorber

Polished surface ($e \sim 0.01$)
– poor emitter / absorber,
good reflector

Water ($e \sim 0.96$)   Earth ($e \sim 0.3$)



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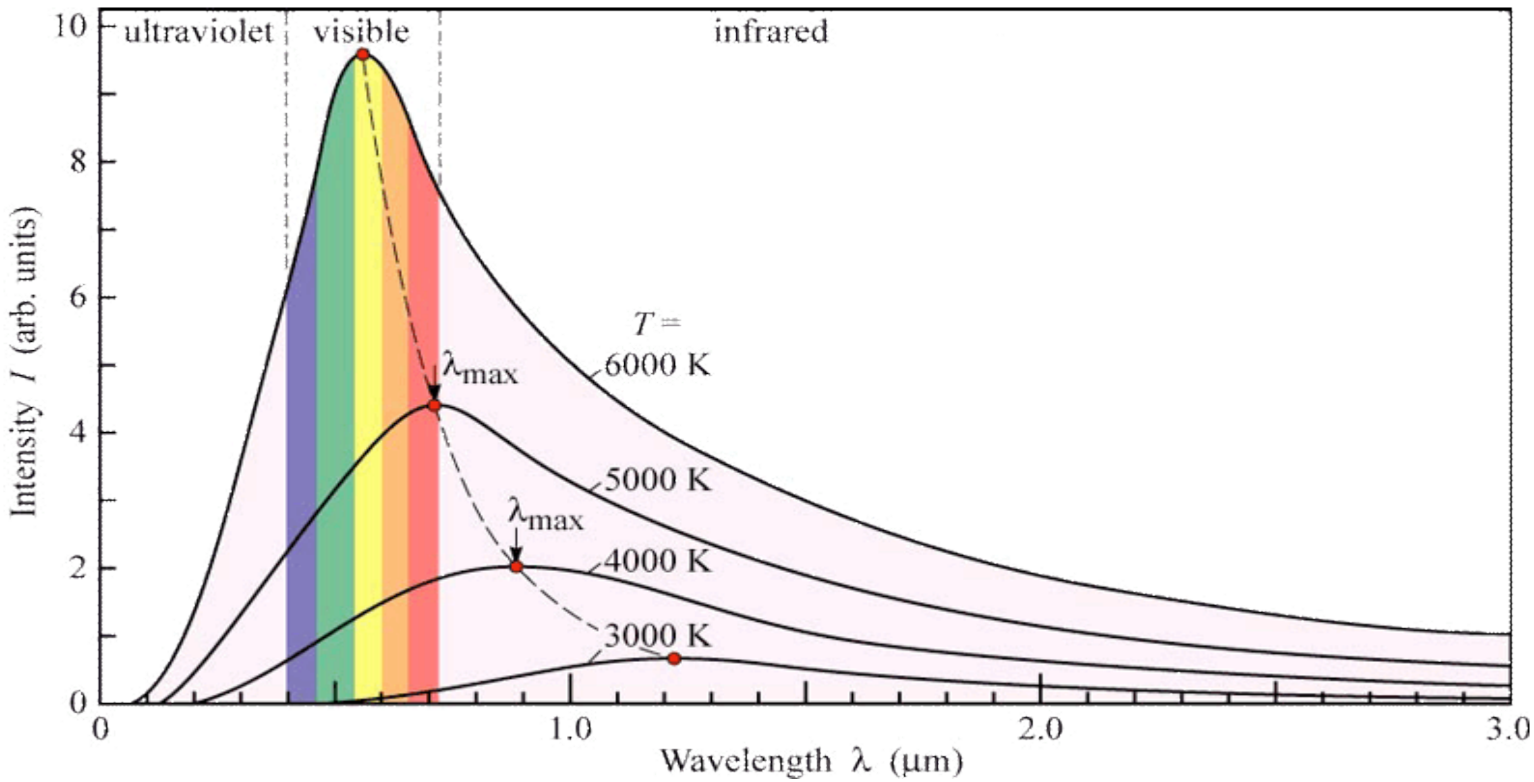
Black body

A *blackbody* absorbs all the radiation incident upon it and emits the max possible radiation at all wavelengths ($e = a = 1$).

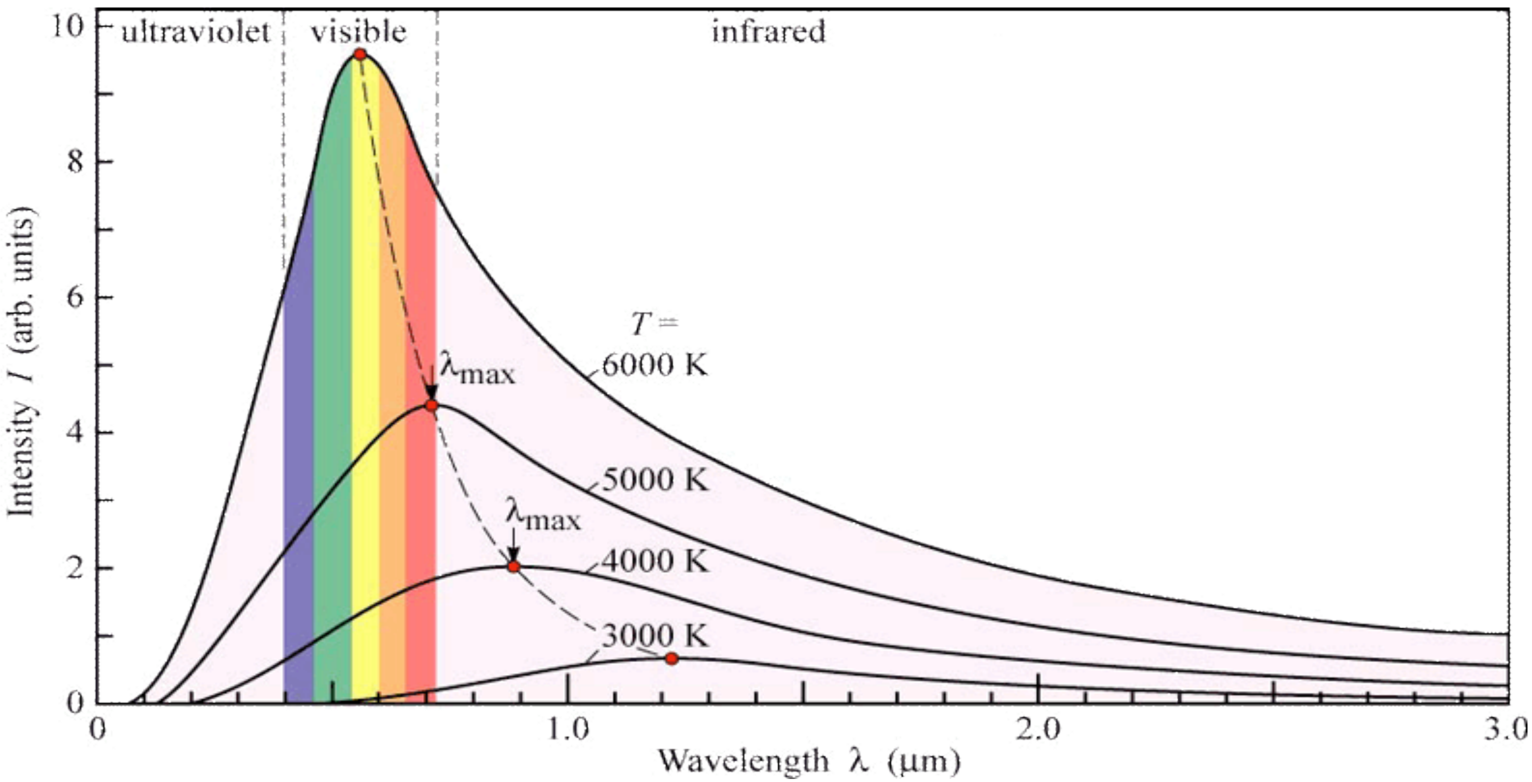


A blackbody radiates at every wavelength.

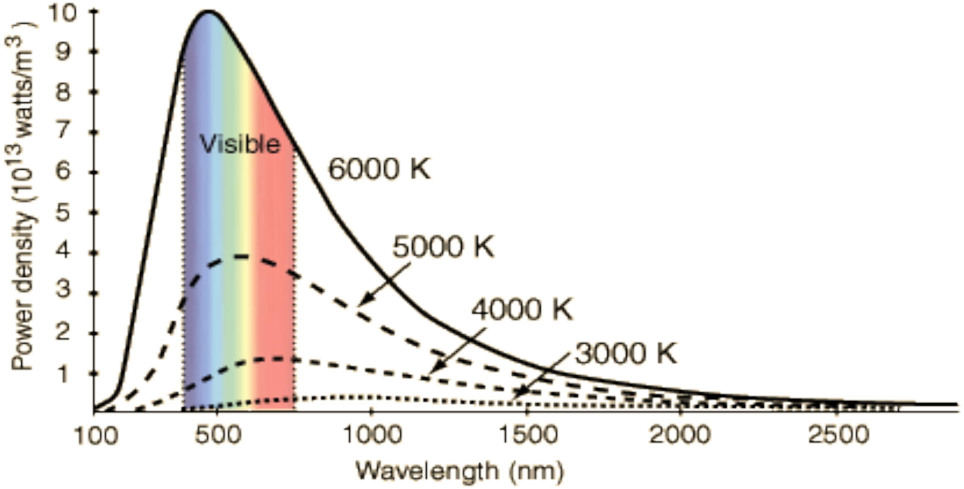
The *peak* wavelength changes with temperature:

$$\lambda_{\text{peak}} = \frac{b_\lambda}{T} \text{ where } b_\lambda = 2.898 \times 10^{-3}\ \text{m.K}$$

(Wien's Displacement Law)

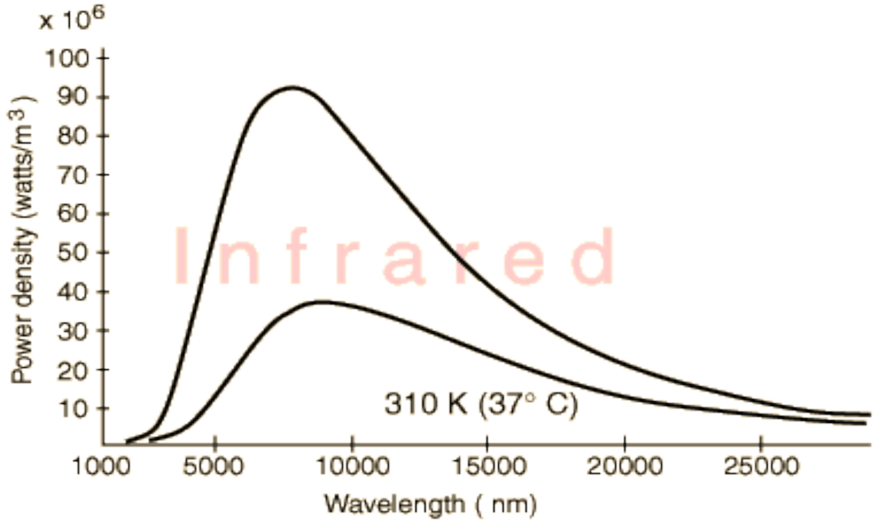


Sun (6000 K – hot!)



Visible radiation

Earth (300 K – cold!)



Infrared radiation

Problem

An igloo is a hemispherical enclosure built of ice. Elmo's igloo has an inner radius of 2.55 m and the thickness of the ice is 0.30 m. This thickness can be considered small compared to the radius. Heat leaks out of the igloo at a rate determined by the thermal conductivity of ice, k_{ice} = 1.67 $W.m^{-1}.K^{-1}$.

At what rate must thermal energy be generated inside the igloo to maintain a steady air temperature inside the igloo at 6.5 °C when the outside temperature is –40 °C?

Ignore all thermal energy losses by conduction through the ground, or any heat transfer by radiation or convection or leaks.

Next lecture

The ideal gas equation of state

Read: YF §18.1