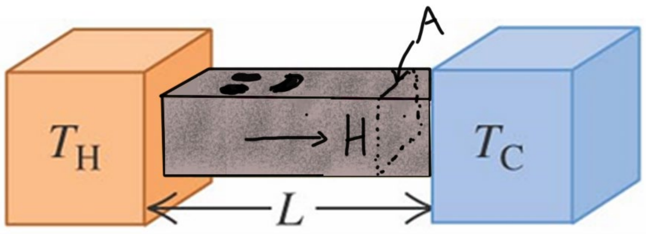
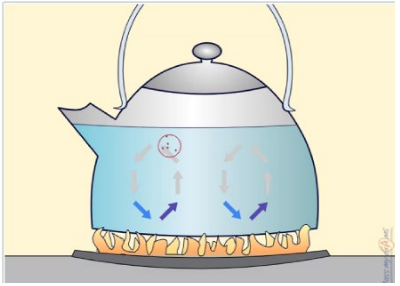
Announcement

- Week 5: There is no class on Monday.
- Week 6:There is no class on Monday, but there will be classes on Wed, Thu, Fri (here at Hebb 100, at 13:00)

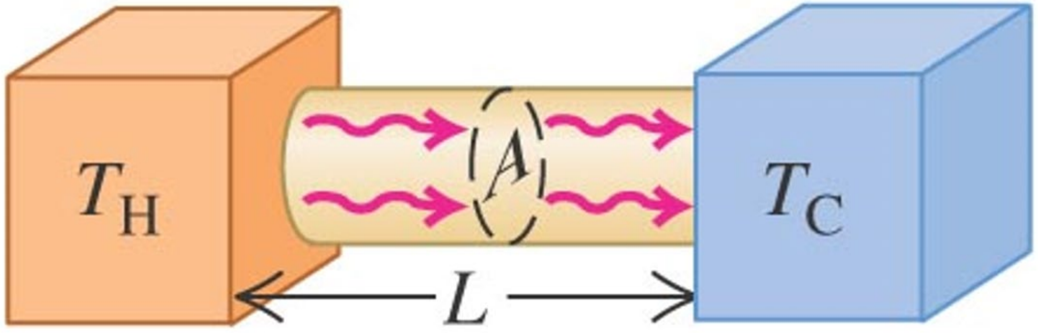


Lecture 11.
Three ways of heat transfer.



Last Time:

Heat current model



heat conduction

driving

$$H = \frac{Q}{\Delta t} = k\,A\,\frac{(T_H - T_C)}{L}$$

material

geometry of sample

- H = Heat current, or heat flow (Joules/second)
- k = Thermal conductivity, a basic property of a material (material constant)
- A = cross sectional area through which heat flows
- $\frac{T_H - T_C}{L}$ = temperature gradient (calculus version: dT/dx)

Thermal Conductivity of Some Common Substances

Substance	k (W/m·K)
Silver	406
Copper	385
Aluminum	205
Wood	0.12 – 0.04
Concrete	0.8
Fiberglass	0.04
Styrofoam	0.027







Application: Insulation

Q: There are two houses, 1 an 2. The second house has insulation that is twice as thick and made with a material that has half the thermal conductivity. To maintain the same inside temperature, the amount of fuel needed to be burned by the furnace in the second house is:

4

A. The same
B. 1/2 as much
C. 1/4 as much
D. 1/8 as much
E. 1/16 as much

$$H = \frac{Q}{\Delta t} = \frac{k A \Delta T}{L}$$

$$H = k\,A\,\frac{T_H - T_C}{L}$$

Application: Insulation

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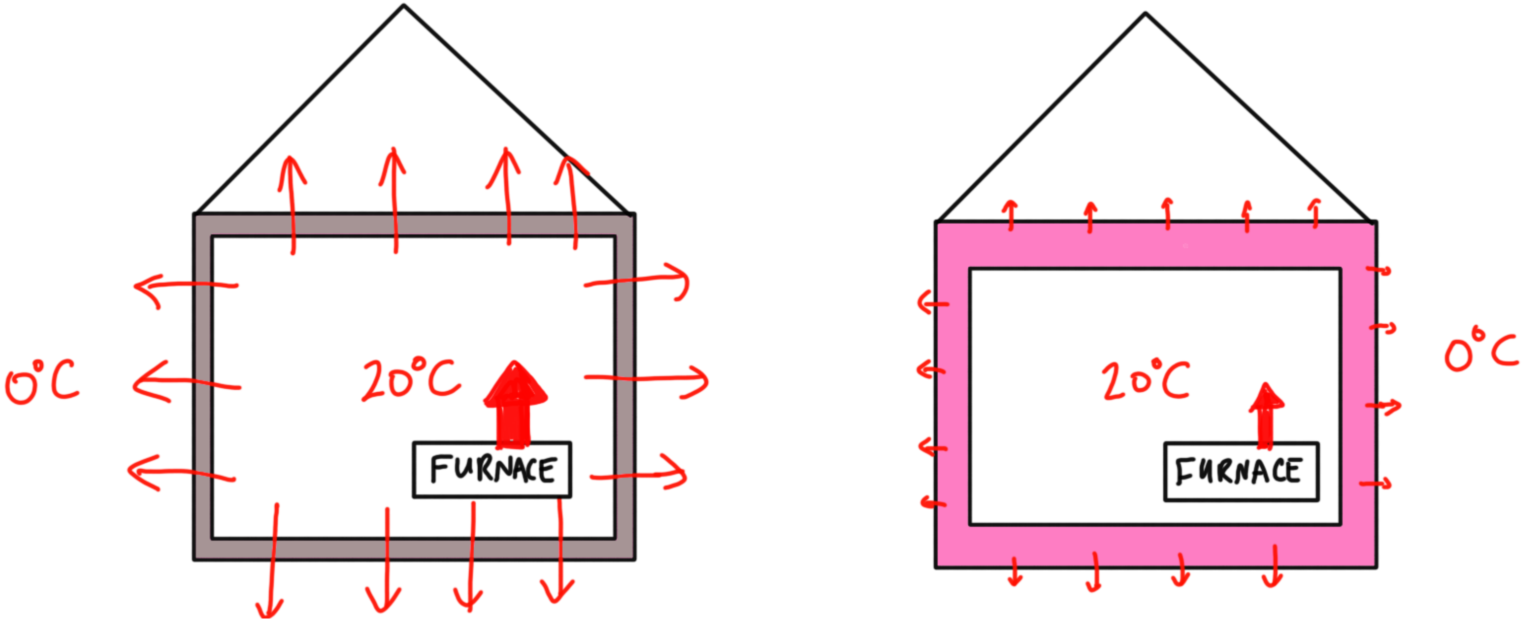
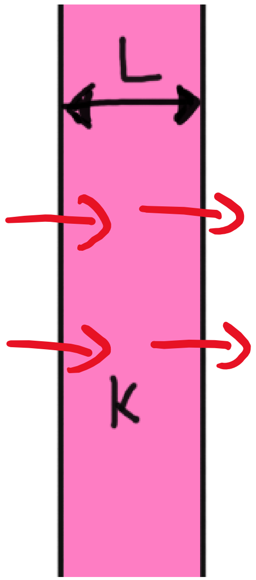


Constant T in house, so $H_{\text{furnace}} = H_{\text{through walls}}$

L is double, k is half, so H is 1/4

$$H = k\,A\,\frac{T_H - T_C}{L}$$

Thermal Resistance ("R-value")

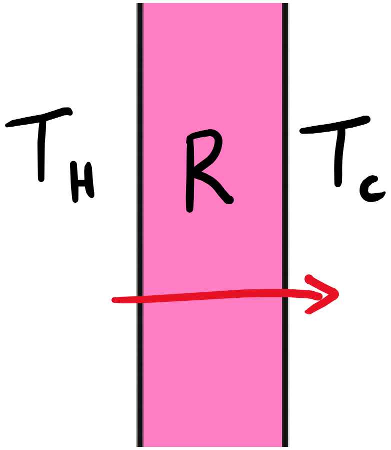


- $R = \frac{L}{k}$ R-value
- L = heat propagation thickness
- k = thermal conductivity

- R-value: measures effectiveness of insulation layer
- Larger R is better!
- Units:
  - SI units are $\mathrm{Km^2/W}$.
  - Imperial: $\mathrm{ft}^2 \cdot {}^{\mathrm{o}}\mathrm{F} \cdot \frac{\mathrm{hours}}{\mathrm{BTU}}$, with $1\,\frac{\mathrm{BTU}}{\mathrm{hour}} = 0.293\ \mathrm{W}$

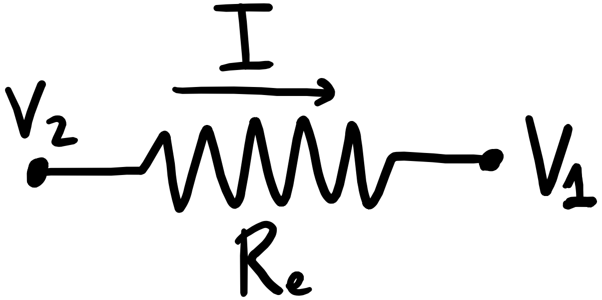
$$\boxed{H = k\,A\,\frac{T_H - T_C}{L} = A\,\frac{T_H - T_C}{R}}$$

Analogy with electrical resistance and Ohm's Law:



$$\boxed{\frac{H}{A} = \frac{T_H - T_C}{R_{th}}}$$

- $\frac{H}{A}$ = heat current per unit area
- R = thermal resistance (L/k)

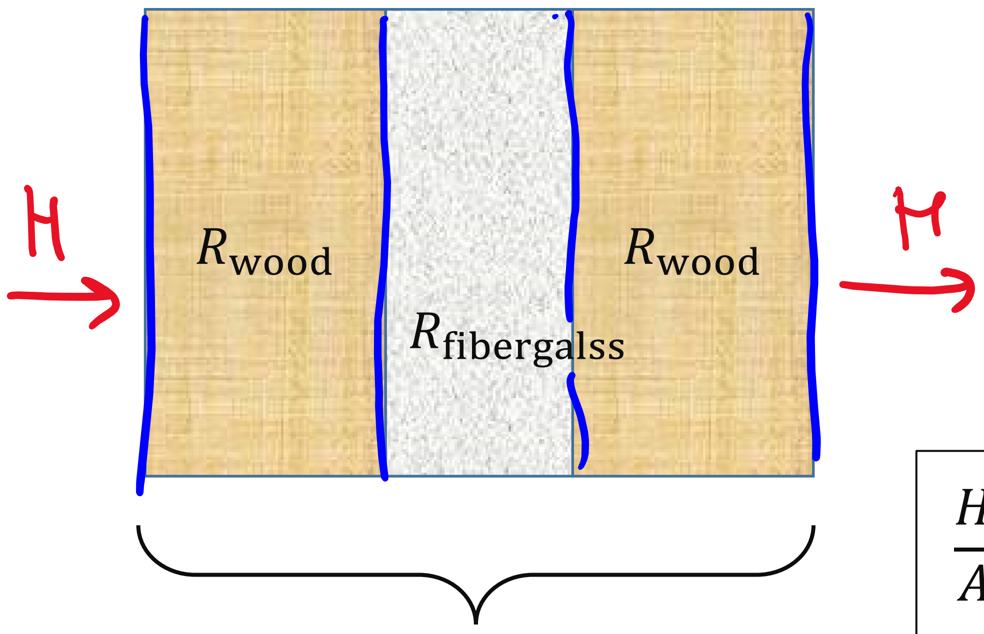


$$\boxed{I = \frac{V_2 - V_1}{R_{el}}}$$

- I= electrical current
- R = electrical resistance

Why R-values, not thermal conductivity k?

- Multiple layers add R-values (like resistors in series)!
- Assuming same area of all consecutive layers:



$$R = 0.87 + 10.9 + 0.87 = 12.64$$

$$\frac{H}{A} = \frac{T_H - T_C}{R}$$

Material	R value (ft²·°F·hr/BTU)
Hardwood siding (1 in. thick)	0.91
Wood shingles (lapped)	0.87
Brick (4 in. thick)	4
Concrete block (filled cores)	1.93
Fiberglass batting(3.5 in. thick)	10.9
Fiberglass batting(6 in. thick)	18.8
Fiberglass board (1 in. thick)	4.35
Cellulose fiber(1 in. thick)	3.7
Flat glass (0.125 in thick)	0.89
Insulating glass(0.25 in space)	1.54
Air space (3.5 in. thick)	1.01
Free stagnant air layer	0.17
Drywall (0.5 in. thick)	0.45
Sheathing (0.5 in. thick)	1.32

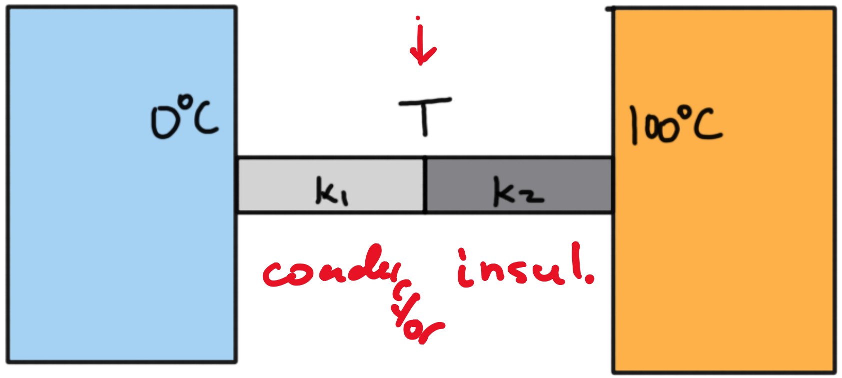
Q: Two materials of equal dimensions but different thermal conductivities are placed side to side between objects kept at 0 °C and 100 °C, and a steady heat flow is established.

If $k_1 > k_2$, we can say that the temperature T in the middle is:

A. Equal to 50 °C

B. Greater than 50 °C

C. Less than 50 °C



heat

k = conductivity

Q: How would you calculate the temperature?

$$H = k\,A\,\frac{T_H - T_C}{L}$$

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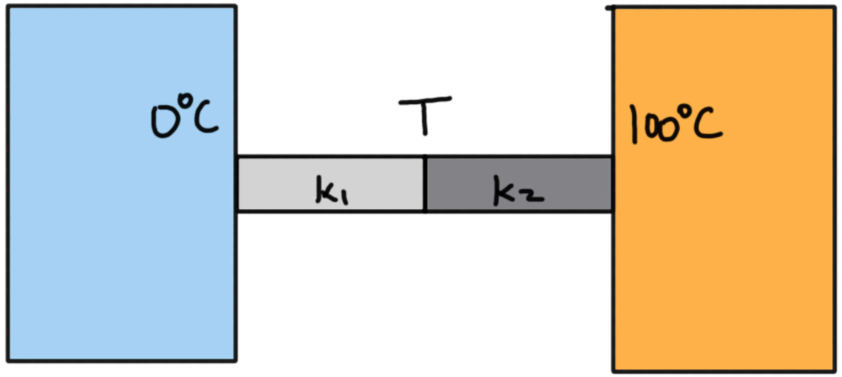


Qualitatively: Think of extreme cases

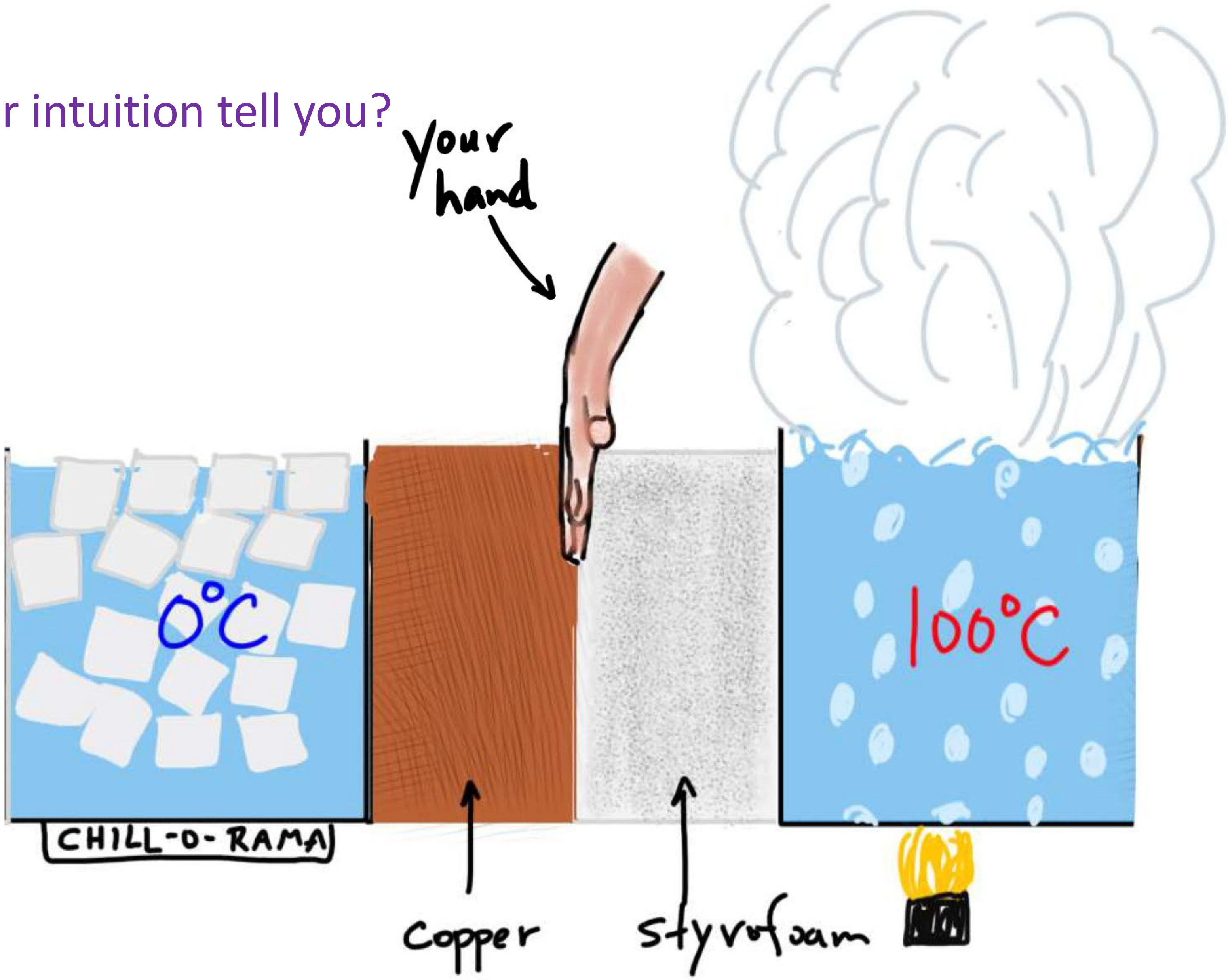
- if k_2 is an almost perfect insulator, T will be almost 0 °C in steady state situation

Q: How would you calculate the temperature?

$$\boxed{H = k\,A\,\frac{T_H - T_C}{L}}$$

What does your intuition tell you?

A. 1 ^{o}C
B. 25 ^{o}C
C. 50 ^{o}C
D. 75 ^{o}C
E. 99 ^{o}C

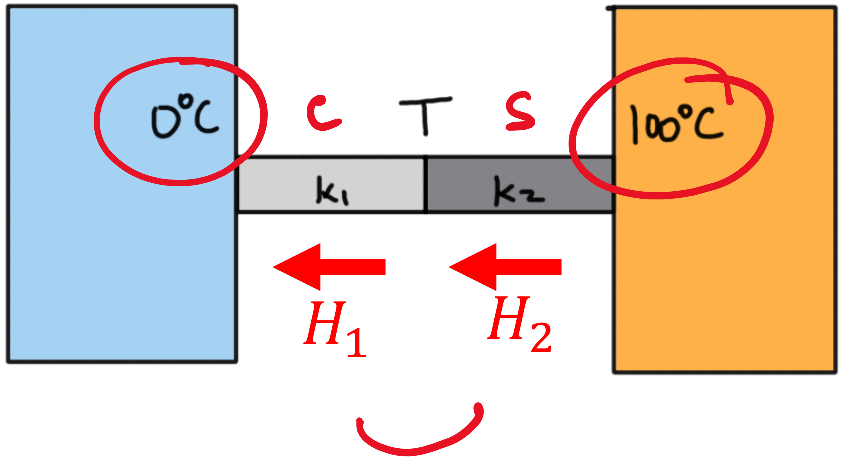


Q: Two materials of equal dimensions but different thermal conductivities are placed side to side between objects kept at 0 °C and 100 °C.

Calculate T in terms of k_1 and k_2.

$k_1 \gg k_2$

$k_1 > k_2$



const

$$H = k\,A\,\underbrace{\frac{T_H - T_C}{L}}$$

- *How do H_1 and H_2 vary in time and how are they related to each other?*

➢ Energy conservation & steady flow $\Rightarrow$ $H_1 = H_2$ and constant in time

Solution:

Copper: $k_c = 385\,\frac{\mathrm{W}}{\mathrm{mK}}$

Styrofoam: $k_s = 0.027\,\frac{\mathrm{W}}{\mathrm{mK}}$,

A. 1 °C

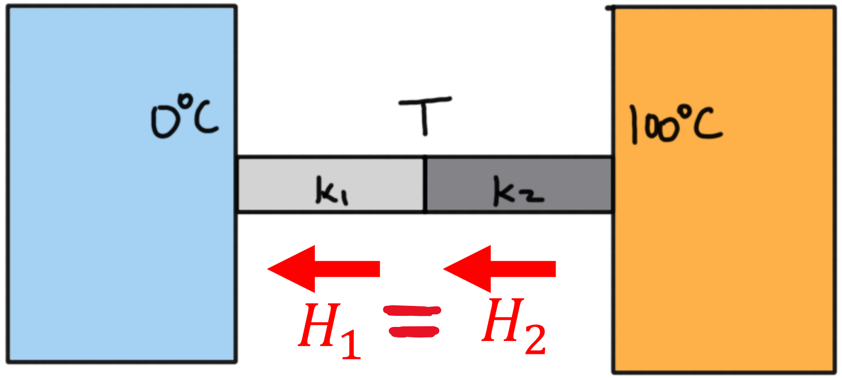
B. 25 °C

C. 50 °C

D. 75 °C

E. 99 °C

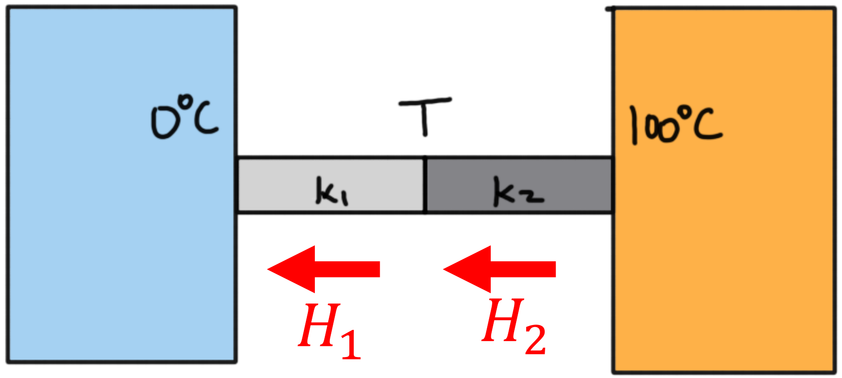
$$k_1 > k_2$$



$$\left(\frac{k_1 A}{L}(T - 0^\circ) = H_1\right) = \left(H_2 = \frac{k_2 A}{L}(100^\circ\mathrm{C} - T)\right)$$

$$\boxed{H = k\,A\,\frac{T_H - T_C}{L}}$$

Solution:



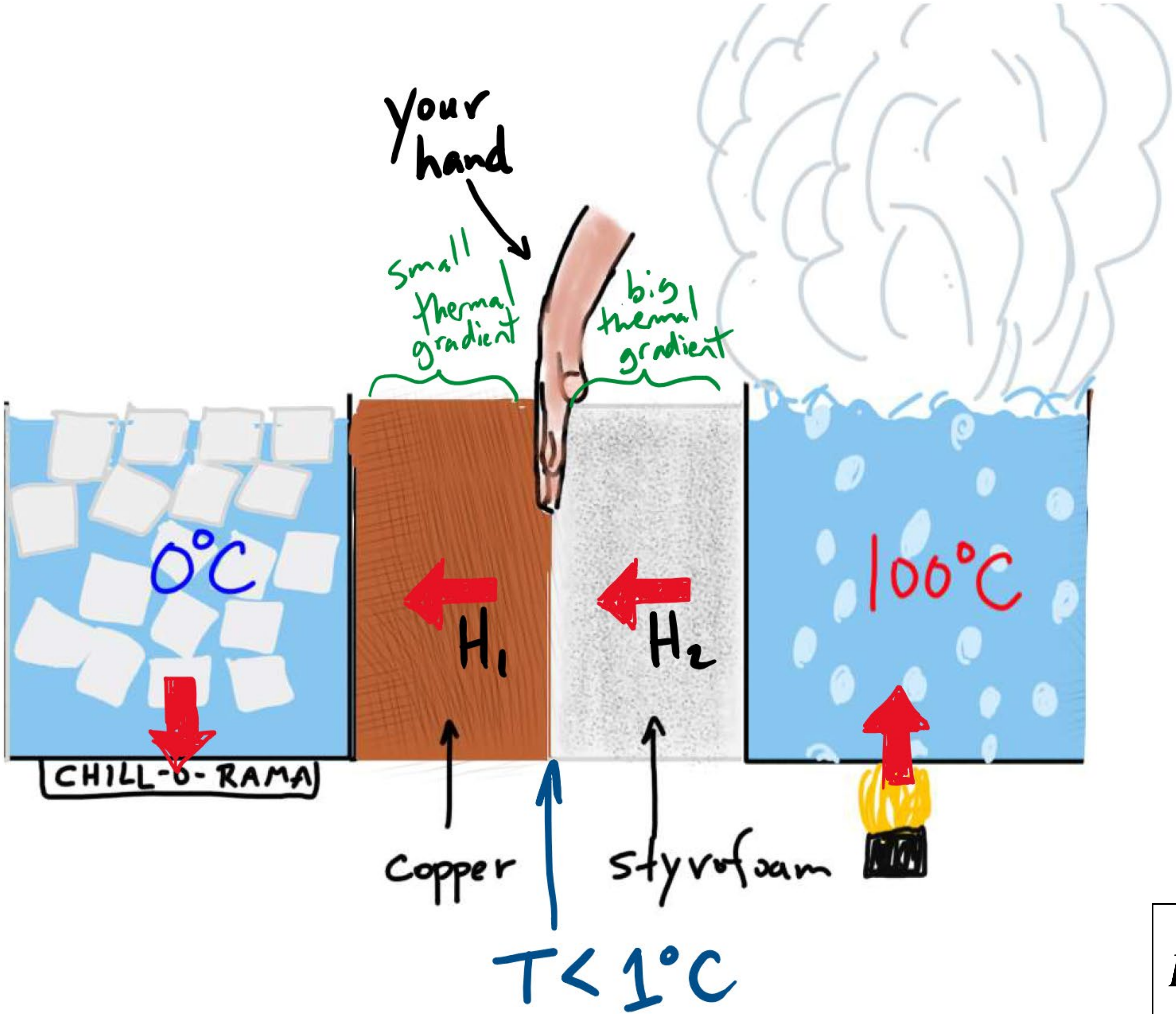
$$k_1 > k_2$$

- Energy conservation & steady flow $\Rightarrow$ $H_1 = H_2$
- $H_1 = k_1 \cdot A \cdot \frac{T - 0\ ^{o}C}{L} = H_2 = k_2 \cdot A \cdot \frac{100\ ^{o}C - T}{L}$
- $k_1(T - 0^{o}C) = k_2(100^{o}C - T)$
- Solving: $T = 100 \frac{k_2}{k_1 + k_2}$
- So T is closer to 0 ^{o}C

k_2 k_1

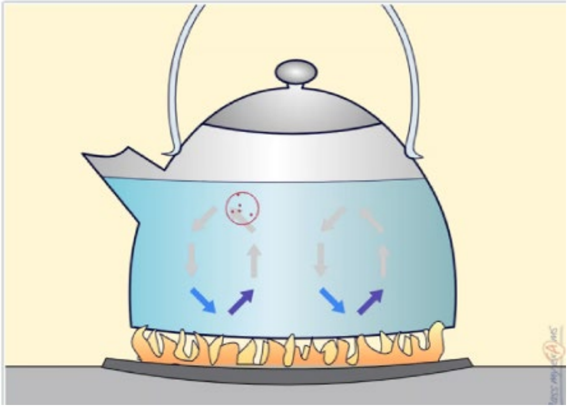
- Styrofoam: $k_s = 0.027 \frac{\mathrm{W}}{\mathrm{mK}}$, copper: $k_c = 385 \frac{\mathrm{W}}{\mathrm{mK}}$ $\Rightarrow$ $T = 0.007$ ^{o}C

$$\boxed{H = k\, A\, \frac{T_H - T_C}{L}}$$



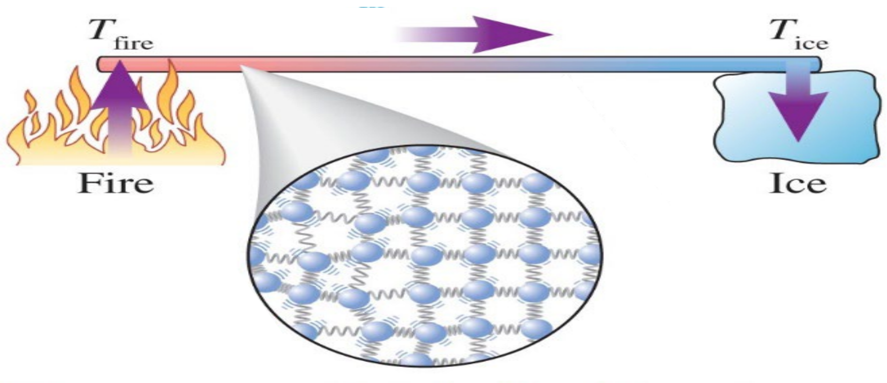
$$H = k\,A\,\frac{T_H - T_C}{L}$$

Convection (just briefly)

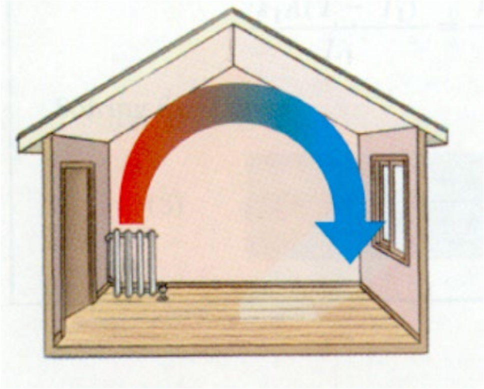


Heat Transfers, or where (and how) Q comes from

- Conduction (what we discussed so far)
  - Heat is transmitted through interactions between neighboring atoms or molecules that vibrate against each other (in solids)



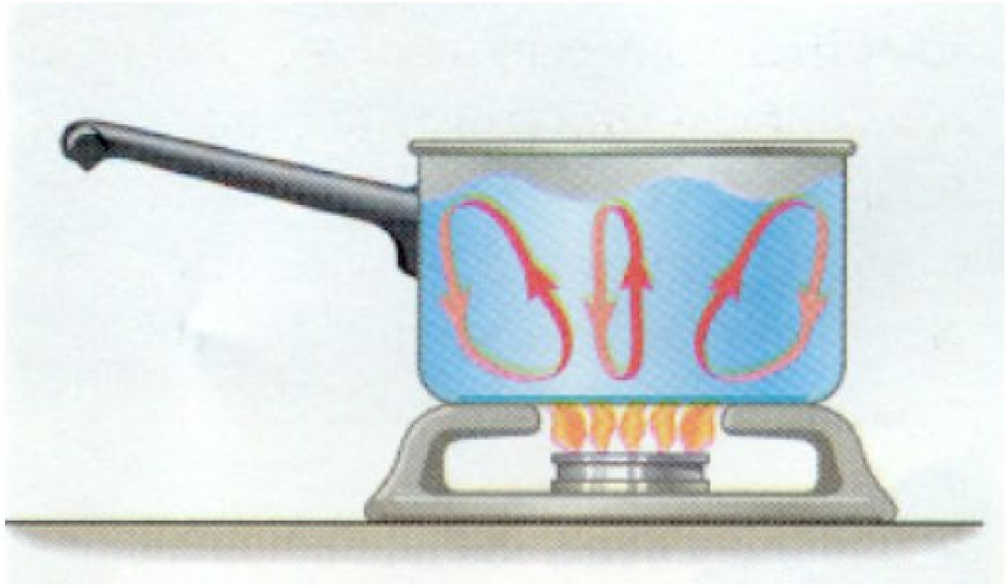
- Convection (next two slides)
  - Heat transfer via macroscopic motion of fluids (fluids = gases or liquids). Very complicated fluid dynamics, difficult to describe.

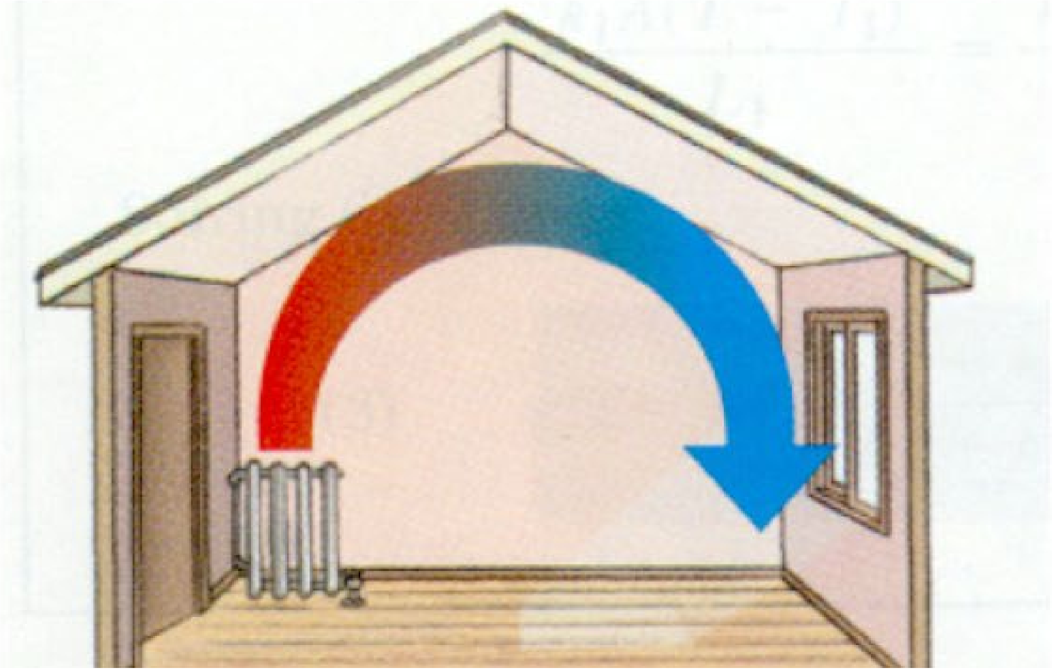


- Radiation (after that)
  - Objects lose (or gain) thermal energy by emitting (or absorbing) electromagnetic radiation.

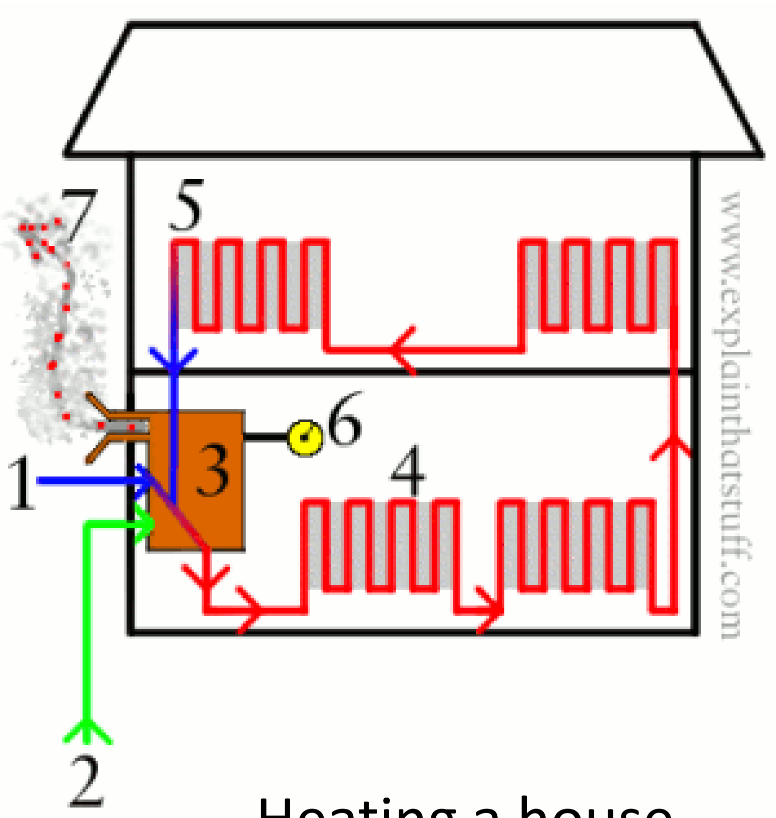
Free convection

- Fluids: gases and liquids
- Fluids have different densities at different temperatures
- Hot fluid expand and then rise / cold fluid shrink and then sink
- Fluid circulates and carries heat with it

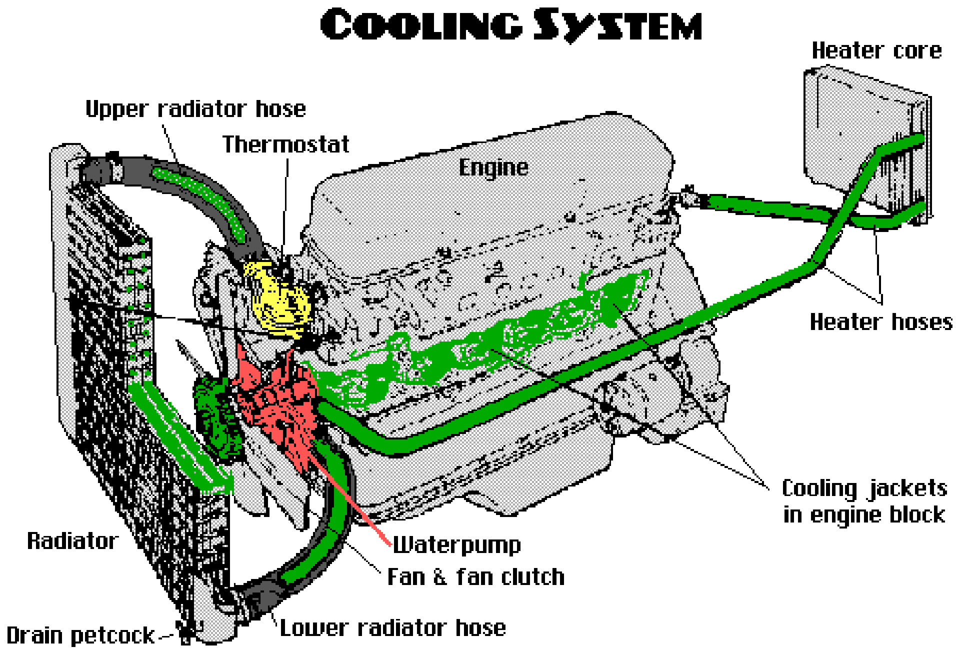




Forced convection



Heating a house



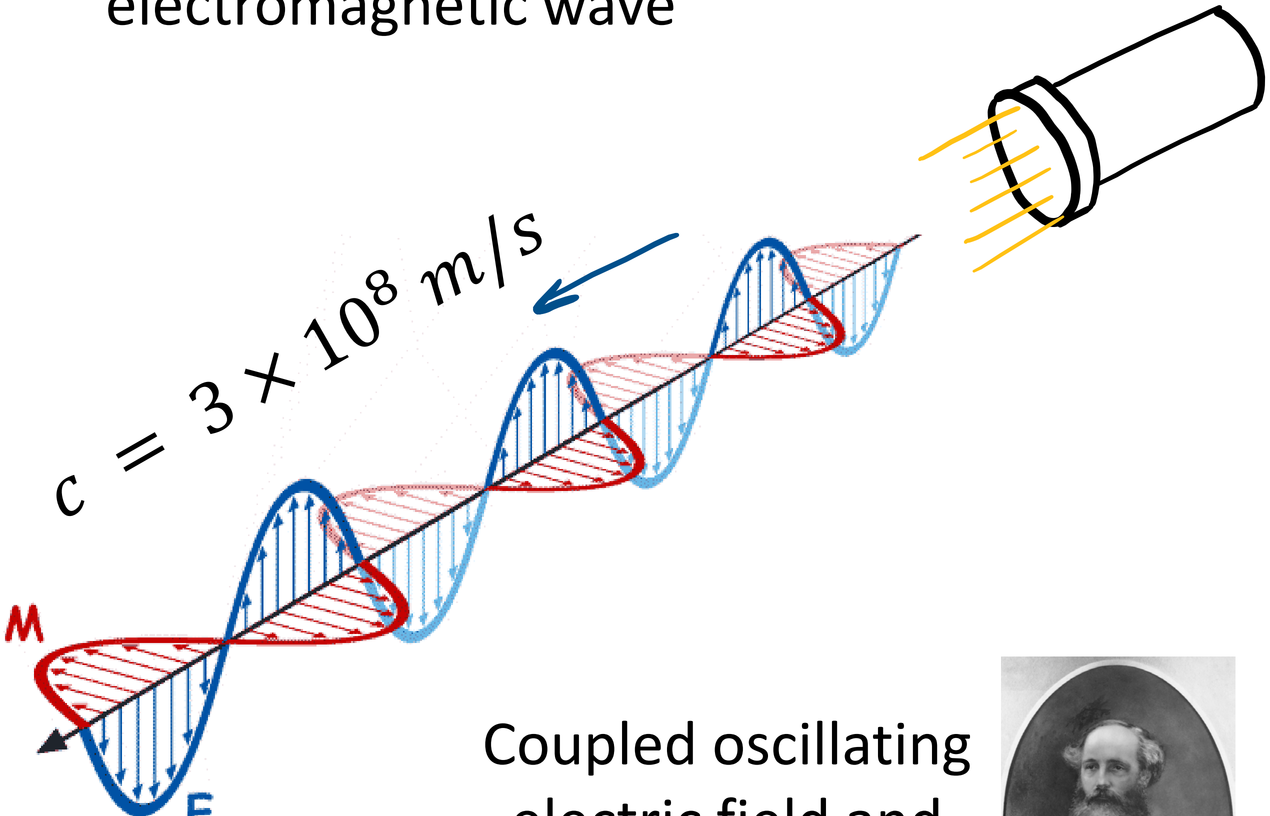
Cooling a car engine and heating the interior

Radiation (a big topic)

Electromagnetic radiation

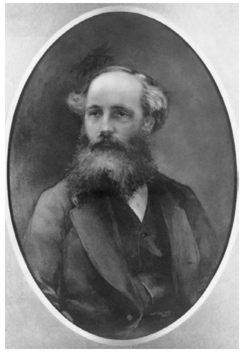
https://en.wikipedia.org/wiki/Electromagnetic_radiation#/media/File:Electromagneticwave3D.gif

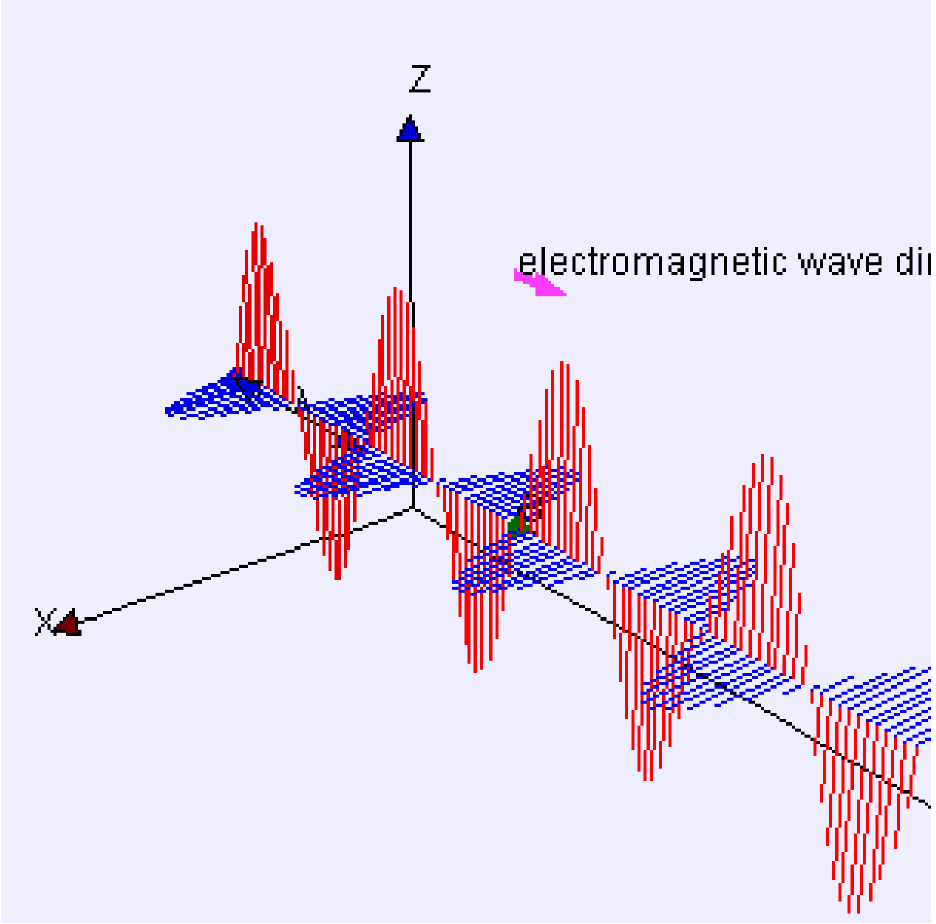
- Light is an example of electromagnetic wave



Coupled oscillating electric field and magnetic field

James Clerk Maxwell 1864

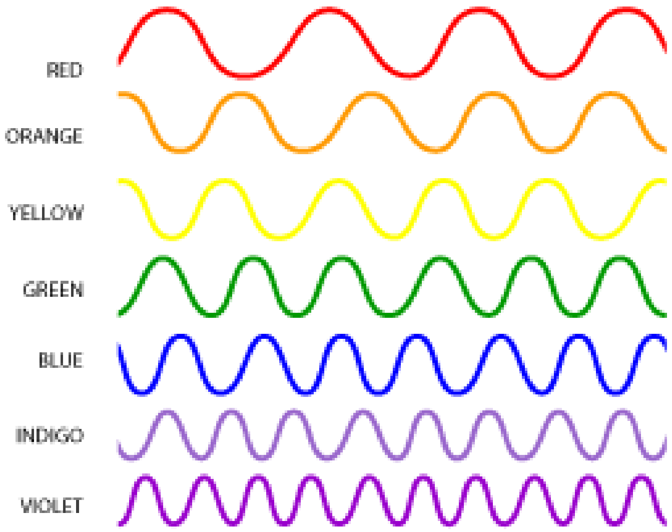




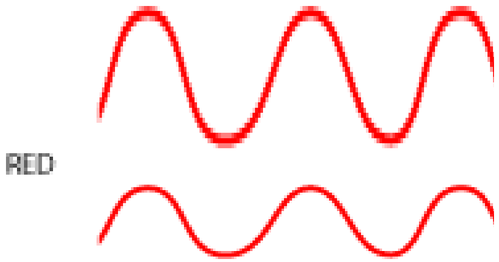
Properties of light

- Speed of light in vacuum: always $c = 3 \times 10^8\ m/s$

- Color: determined by wavelength of visible light



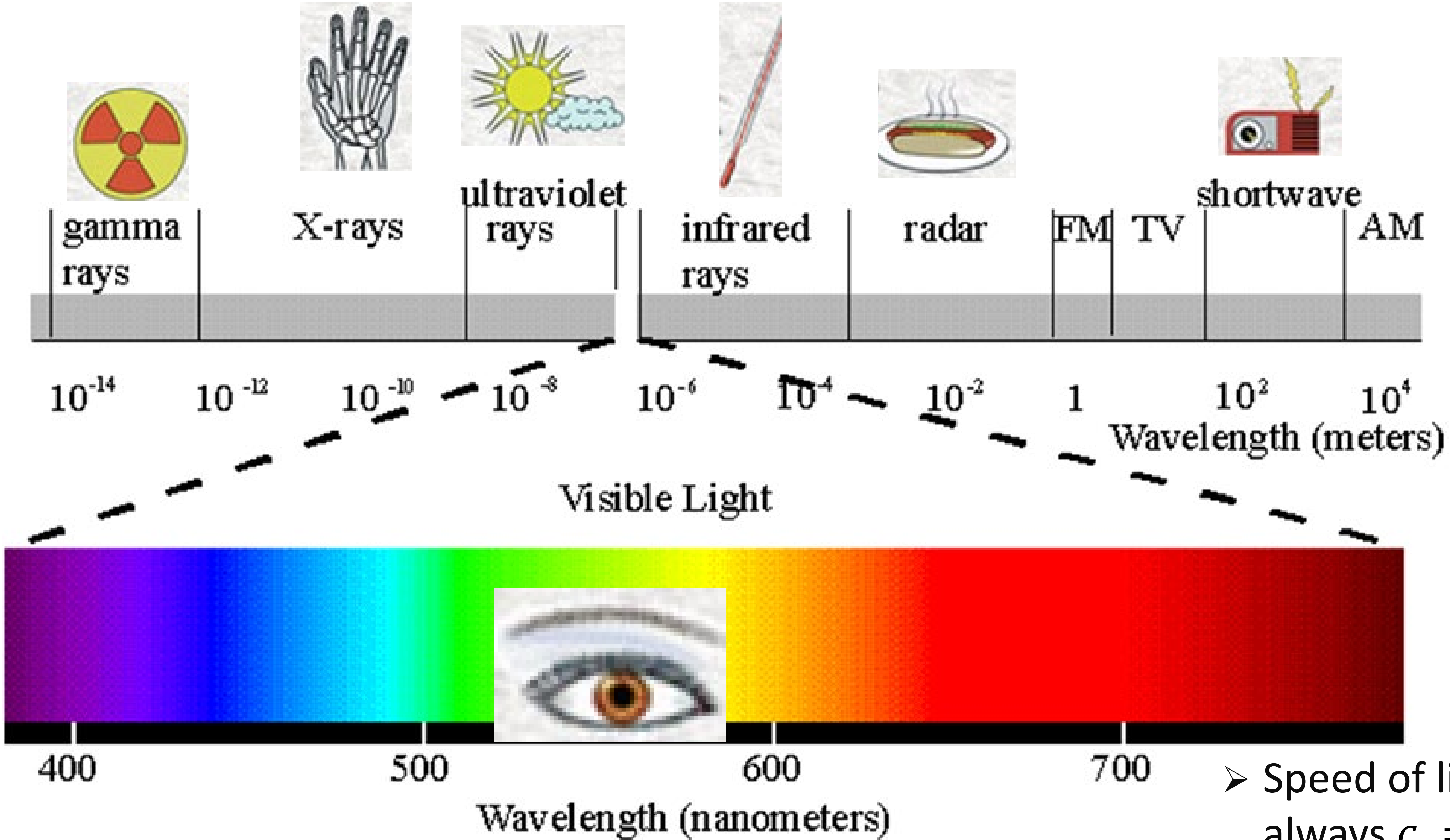
- Intensity/brightness: determined by amplitude



- Amplitude is related to the energy of a wave => light can carry energy!

Electromagnetic waves come at a variety of wavelengths

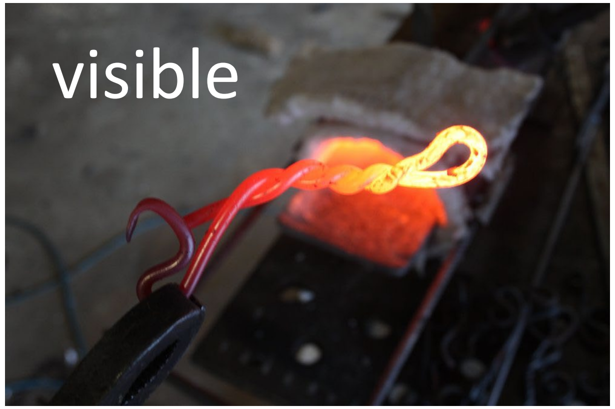
- All electromagnetic waves have the same properties and show the same effects.

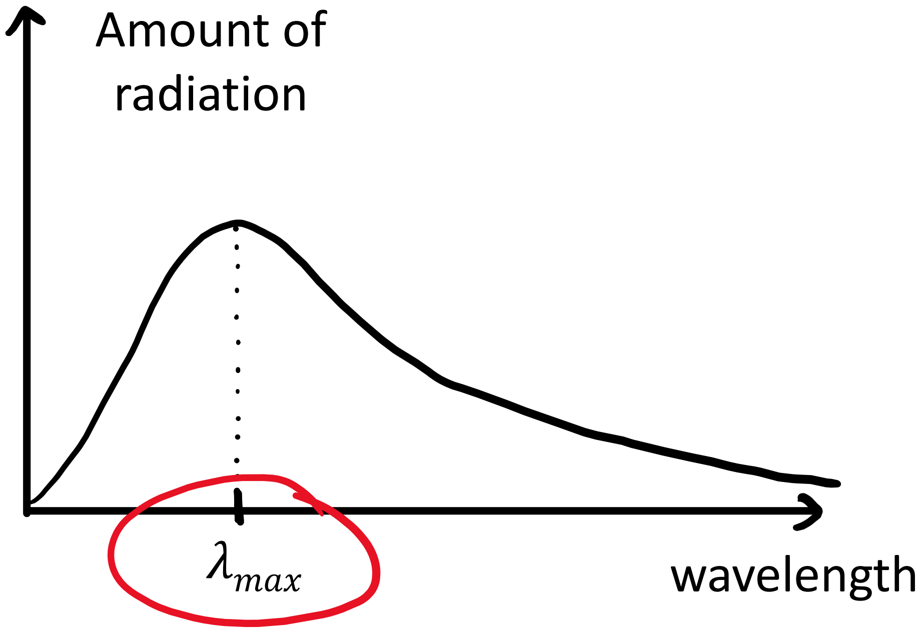


- Speed of light in vacuum: always $c = 3 \times 10^8\ m/s$

Thermal radiation from an object

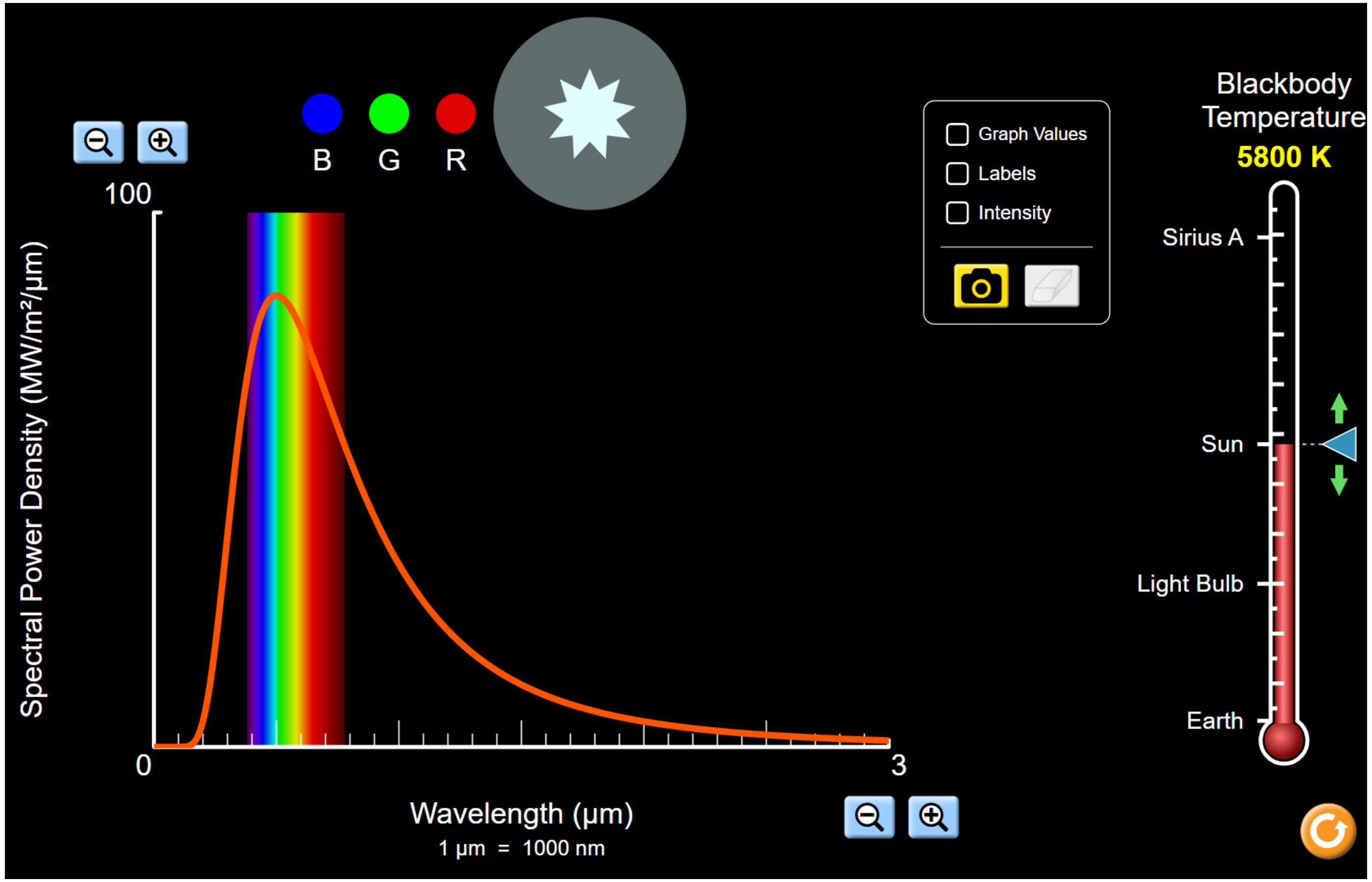
- Each object emits EM waves. It comes in a variety of wavelengths
- Spectrum: measures energy current for various wavelengths
- Typically in IR / visible





Blackbody Spectrum

- In the simulation, what properties of the thermal spectrum change as we change the temperature?



https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html

Demo: nail burner