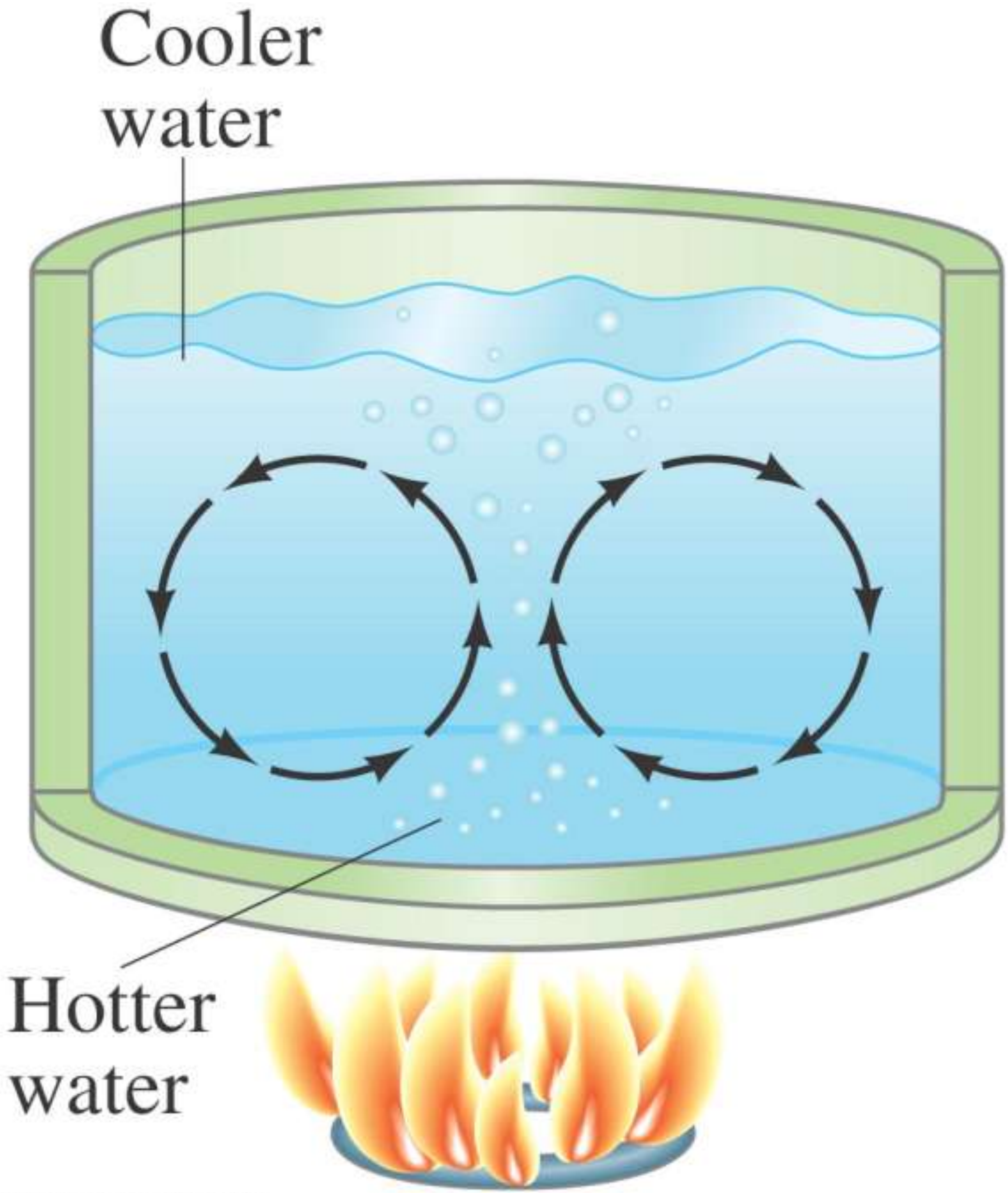
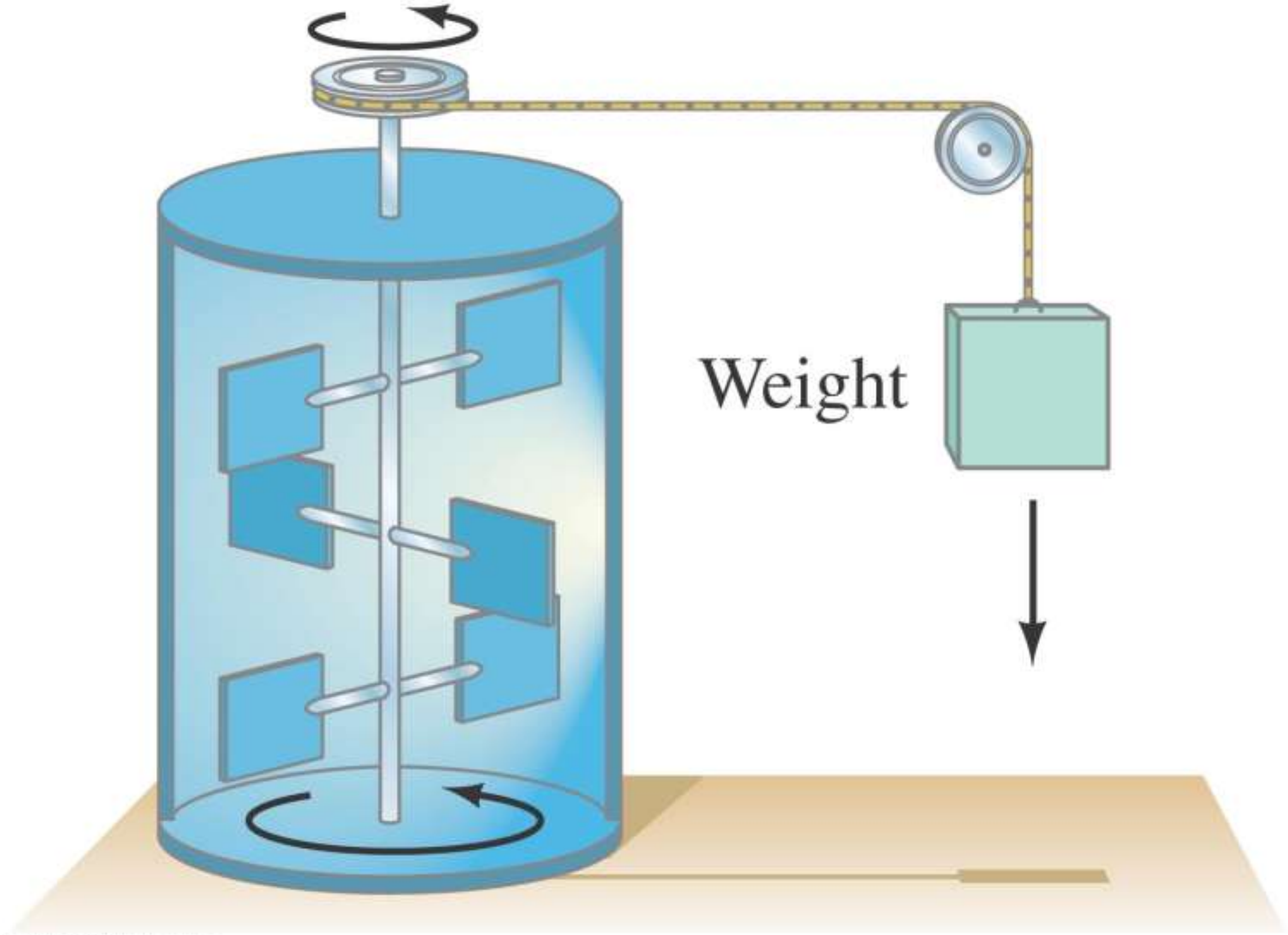
Heat (C19.1-6, 10)

- Temperature (T) is measure of average KE of all molecules
- Internal energy (or Thermal Energy) is sum of total energy of all molecules.
- Heat is transfer of IE from one body to another. Process, not a thing.
- Heat flows from hot to cold.
- $W + Q = \Delta E_{sys}$
- Only consider $Q = \Delta E_{internal}$ no work or mech E



$Q = \Delta E_{\text{internal}}$



Temperature of body can be increased by doing work on it. Here $W = \Delta E \Rightarrow mgh = \Delta E_{internal}$

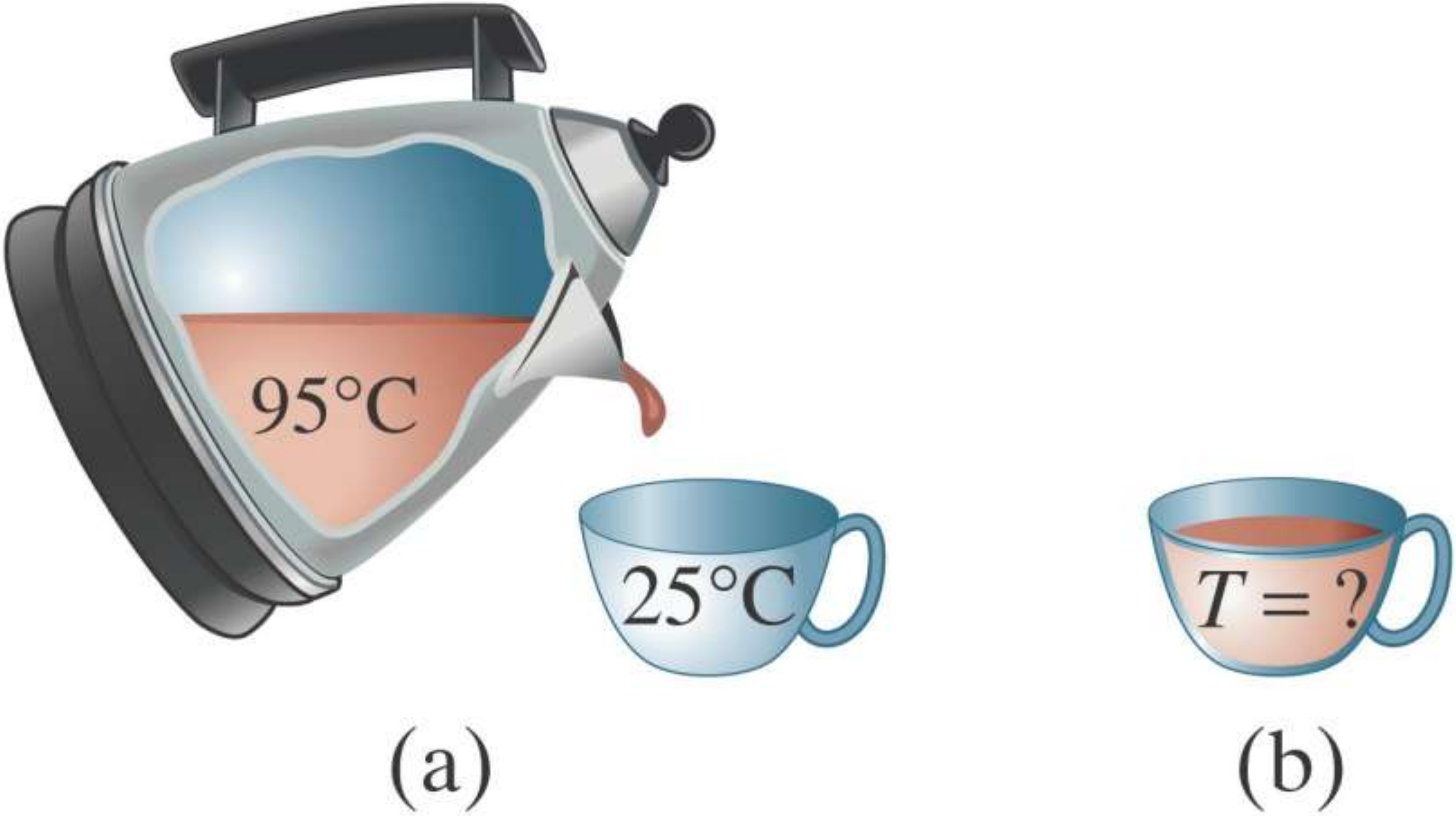
ΔE_{int}

- Bigger mass object has a smaller ΔT than lower mass
- Different materials of same mass will have different ΔT for same Q.
- $\Delta E_{int} = mc\,\Delta T$
- c is specific heat capacity

TABLE 19–1 Specific Heats (at 1 atm constant pressure and 20°C unless otherwise stated)

Substance	Specific Heat, c kcal/kg · C° (= cal/g · C°)	Specific Heat, c J/kg · C°
Aluminum	0.22	900
Alcohol (ethyl)	0.58	2400
Copper	0.093	390
Glass	0.20	840
Iron or steel	0.11	450
Lead	0.031	130
Marble	0.21	860
Mercury	0.033	140
Silver	0.056	230
Wood	0.4	1700
Water		
Ice (−5°C)	0.50	2100
Liquid (15°C)	1.00	4186
Steam (110°C)	0.48	2010
Human body (average)	0.83	3470
Protein	0.4	1700

Calorimetry



How to Find T_f

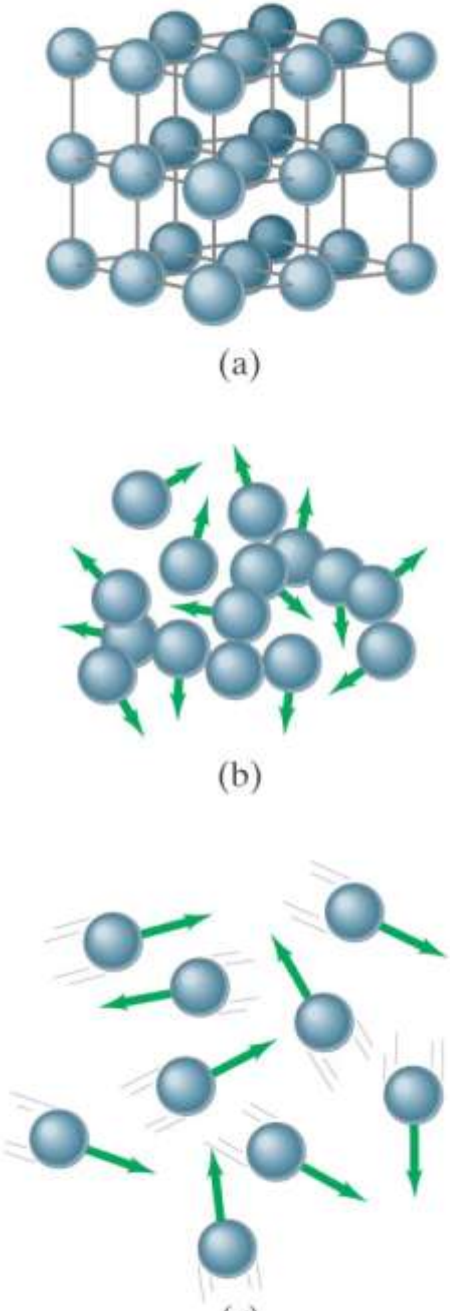
- Can consider coffee and cup as individual systems
- $Q = \Delta E_{int} \Rightarrow$
- $Q_{coffee} = m_{coffee} c_{coffee} \Delta T_{coffee}$ &
- $Q_{cup} = m_{cup} c_{cup} \Delta T_{cup}$
- No loss to environment $Q_{coffee} + Q_{cup} = 0$

How to Find T_f

- Or can consider coffee and cup as one system
- $Q = \Delta E_{int} \Rightarrow$
- $Q = m_{coffee} c_{coffee} \Delta T_{coffee} + m_{cup} c_{cup} \Delta T_{cup}$
- No loss to environment $Q = 0$ or
- $0 = m_{coffee} c_{coffee} \Delta T_{coffee} + m_{cup} c_{cup} \Delta T_{cup}$

- Exactly same result

Phase Changes

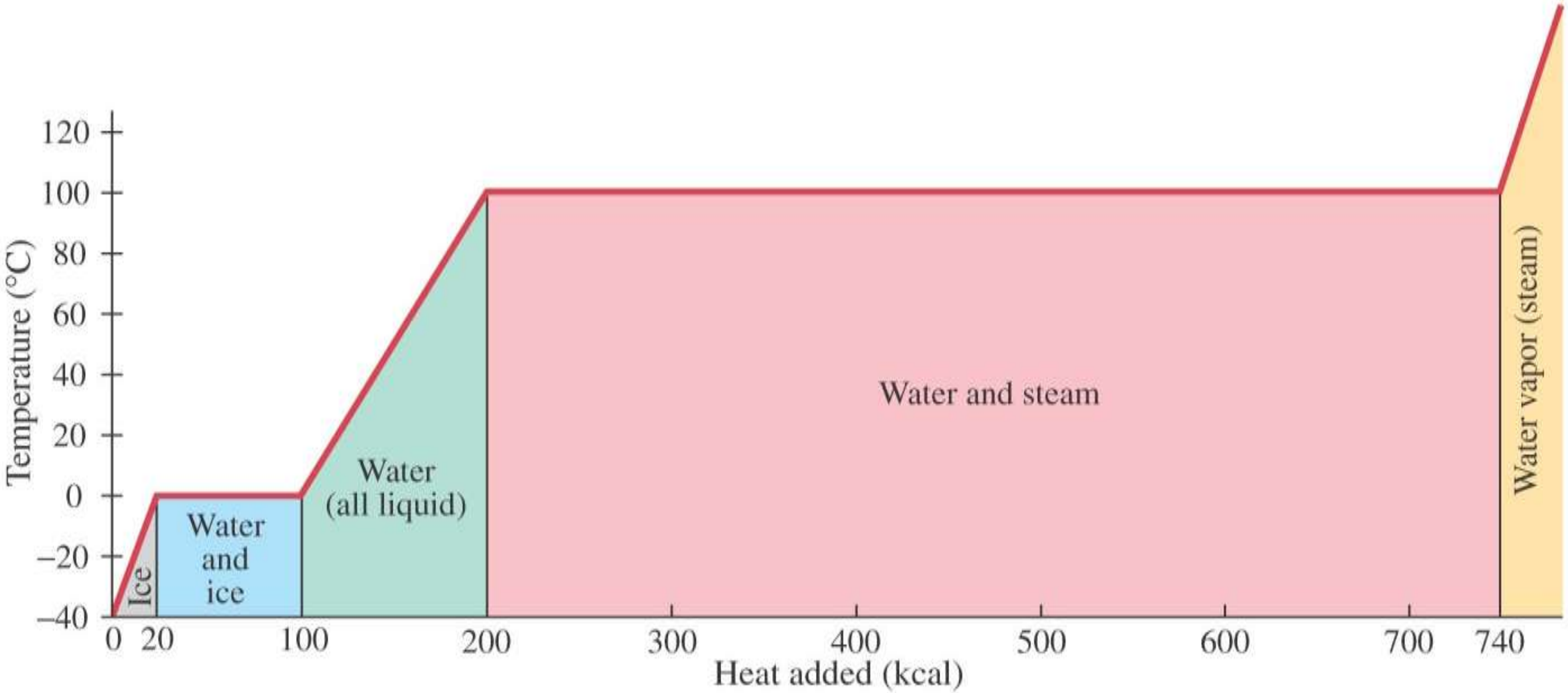


(a)

(b)

(c)

- When you warm ice to 0 C, need to add energy to break bonds to get water at 0 C.
- Ice cannot have T > 0 C
- When you heat water to 100 C, need to add energy to break bonds to get steam at 100 C.
- Water cannot have T > 100 C
- Cooling releases energy


Temperature (°C)
120
100
80
60
40
20
0
−20
−40
Ice
Water and ice
Water (all liquid)
Water and steam
Water vapor (steam)
0
20
100
200
300
400
500
600
700
740
Heat added (kcal)

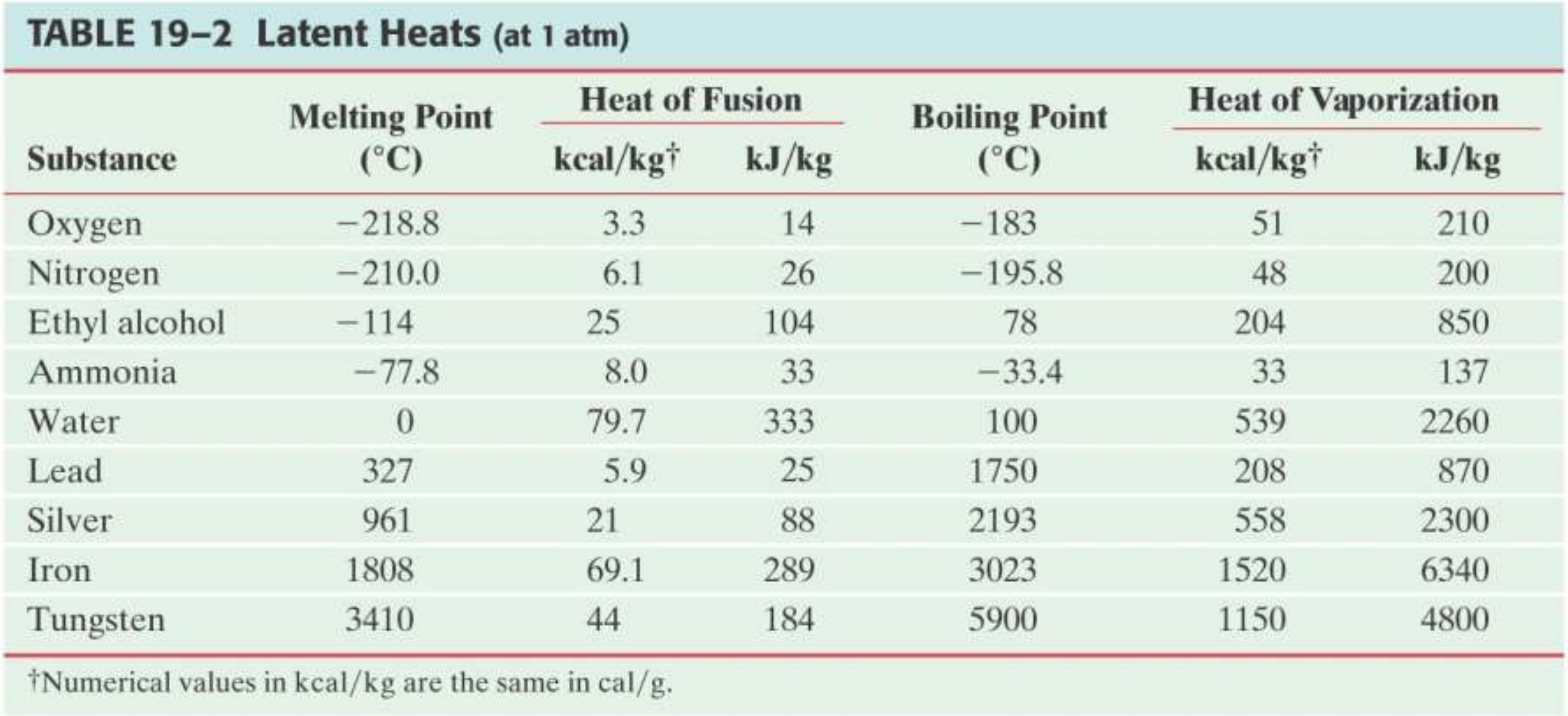


TABLE 19–2 Latent Heats (at 1 atm)

Substance	**Melting Point (°C)**	**Heat of Fusion**		**Boiling Point (°C)**	**Heat of Vaporization**	
		kcal/kg†	**kJ/kg**		**kcal/kg†**	**kJ/kg**
Oxygen	−218.8	3.3	14	−183	51	210
Nitrogen	−210.0	6.1	26	−195.8	48	200
Ethyl alcohol	−114	25	104	78	204	850
Ammonia	−77.8	8.0	33	−33.4	33	137
Water	0	79.7	333	100	539	2260
Lead	327	5.9	25	1750	208	870
Silver	961	21	88	2193	558	2300
Iron	1808	69.1	289	3023	1520	6340
Tungsten	3410	44	184	5900	1150	4800

†Numerical values in kcal/kg are the same in cal/g.

Calorimetry Problems

- Just simple Conservation of Energy problems.
- Note which objects gain energy and which lose.
- Solids cannot get hotter than melting temp.
- Liquids cannot get hotter than boiling temp.

(assuming STP! And no loses to environment)

- Phase changes require lots of energy!

Cooling by Evaporation (Sweating & Panting)

Keeping your cool BIO Humans (and cattle and horses) have sweat glands, so we can perspire to moisten our skin, allowing evaporation to cool our bodies. Animals that do not perspire can also use evaporation to keep cool. Dogs, goats, rabbits, and even birds pant, evaporating water from their respiratory passages. Elephants spray water on their skin; other animals may lick their fur.

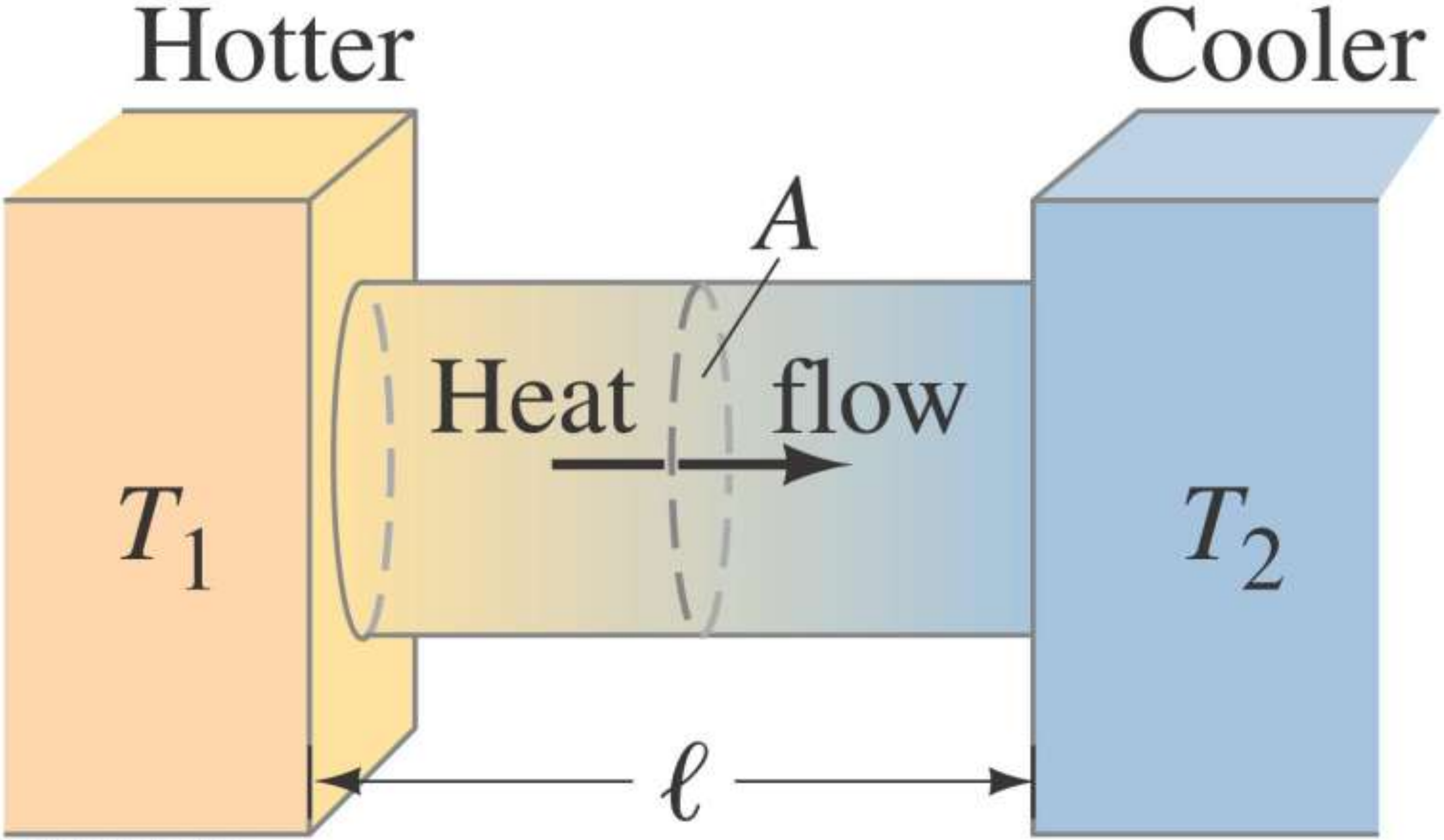
- Boiling ⇔ Fast Evap.
- Only at 100 C (STP)
- Evap. Also occurs at lower T. (spills eventually dry up)
- Evap. Is a cooling process.
- Important for body thermal regulation

- In a liquid, a fast molecule can use KE to break free (evaporate).
- In a liquid, speed is a distribution. A few atoms always have enough KE to leave.
- Hotter liquids have more fast molecules
- When fast molecules leave, E of rest is lower (T has fallen). Remaining liquid is cooler.
- Being cooler than surface (skin), surface loses E to liquid.
- Note air is good insulator, so air doesn’t cool.

- Surface area plays a big role. A ↑, Evap. ↑
- Process can go in reverse. Water molecules in air can condense on a cool surface. Depends on # in air (Humidity) and Temp. Diff between air and surface.
- Humid days feel hotter than dry days of same T, because sweating is less effective.
- Humans excel at sweating b/c of bare skin (no fur or feathers)

- Conversely furry animals pant
- Panting also cools much same way.
- Dry air is inhaled, warm humid breath is exhaled. Lungs are cooled by evap.

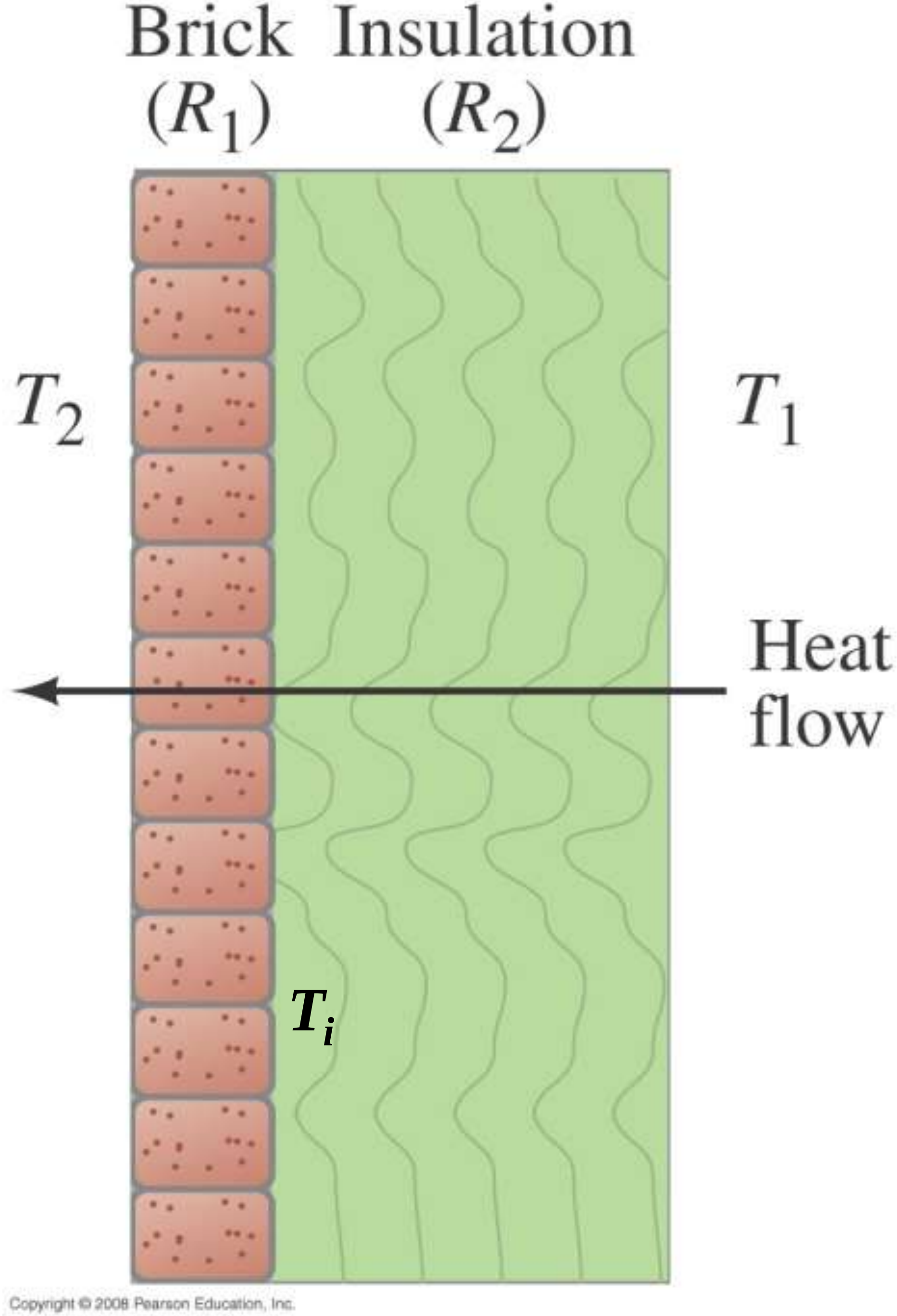
Heat Transfer by Conduction



$P = \frac{\Delta Q}{\Delta t} = \kappa A \frac{(T_{hot}-T_{cool})}{L}$ or $\frac{\Delta Q}{\Delta t} = A \frac{(T_{hot}-T_{cool})}{R}$ where $R = \frac{L}{K}$

TABLE 19–5
Thermal Conductivities

Substance	Thermal conductivity, k	
	$\frac{\text{kcal}}{(\text{s}\cdot\text{m}\cdot\text{C}^\circ)}$	$\frac{\text{J}}{(\text{s}\cdot\text{m}\cdot\text{C}^\circ)}$
Silver	10×10^{-2}	420
Copper	9.2×10^{-2}	380
Aluminum	5.0×10^{-2}	200
Steel	1.1×10^{-2}	40
Ice	5×10^{-4}	2
Glass	2.0×10^{-4}	0.84
Brick	2.0×10^{-4}	0.84
Concrete	2.0×10^{-4}	0.84
Water	1.4×10^{-4}	0.56
Human tissue	0.5×10^{-4}	0.2
Wood	0.3×10^{-4}	0.1
Fiberglass	0.12×10^{-4}	0.048
Cork	0.1×10^{-4}	0.042
Wool	0.1×10^{-4}	0.040
Goose down	0.06×10^{-4}	0.025
Polyurethane	0.06×10^{-4}	0.024
Air	0.055×10^{-4}	0.023



$R_{eq} = R_1 + R_2$

For insulators in series.

Heat flow same through each layer

$$\frac{\Delta Q}{\Delta t} = A\frac{(T_1 - T_i)}{R_2}$$

$$\frac{\Delta Q}{\Delta t} = A\frac{(T_i - T_2)}{R_1}$$

Proof: Can rewrite equations

$$R_2 \frac{\Delta Q}{\Delta t} = A(T_1 - T_i) \qquad R_1 \frac{\Delta Q}{\Delta t} = A(T_i - T_2)$$

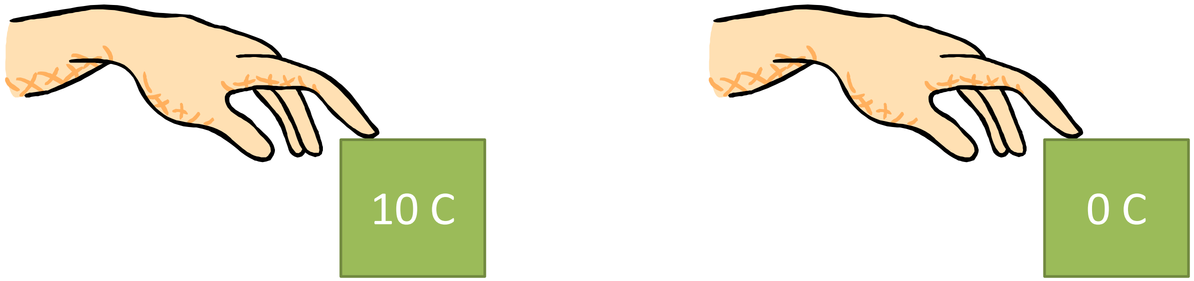
Add equations.

$$(R_1 + R_2)\frac{\Delta Q}{\Delta t} = A(T_1 - T_2) \qquad \frac{\Delta Q}{\Delta t} = A\frac{(T_1 - T_2)}{(R_1 + R_2)} \qquad \frac{\Delta Q}{\Delta t} = A\frac{(T_1 - T_2)}{R_{equivalent}}$$

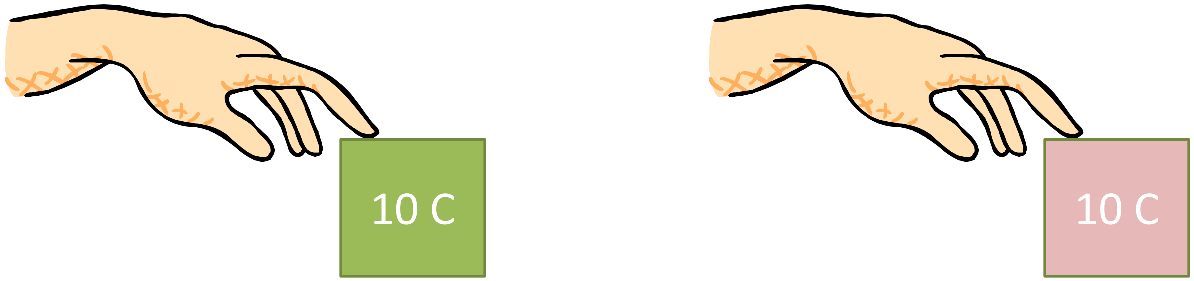
If you want to find the temperature of the boundary:

$$A\frac{(T_1 - T_i)}{R_1} = A\frac{(T_i - T_2)}{R_2}$$

Our Sense of Hot and Cold



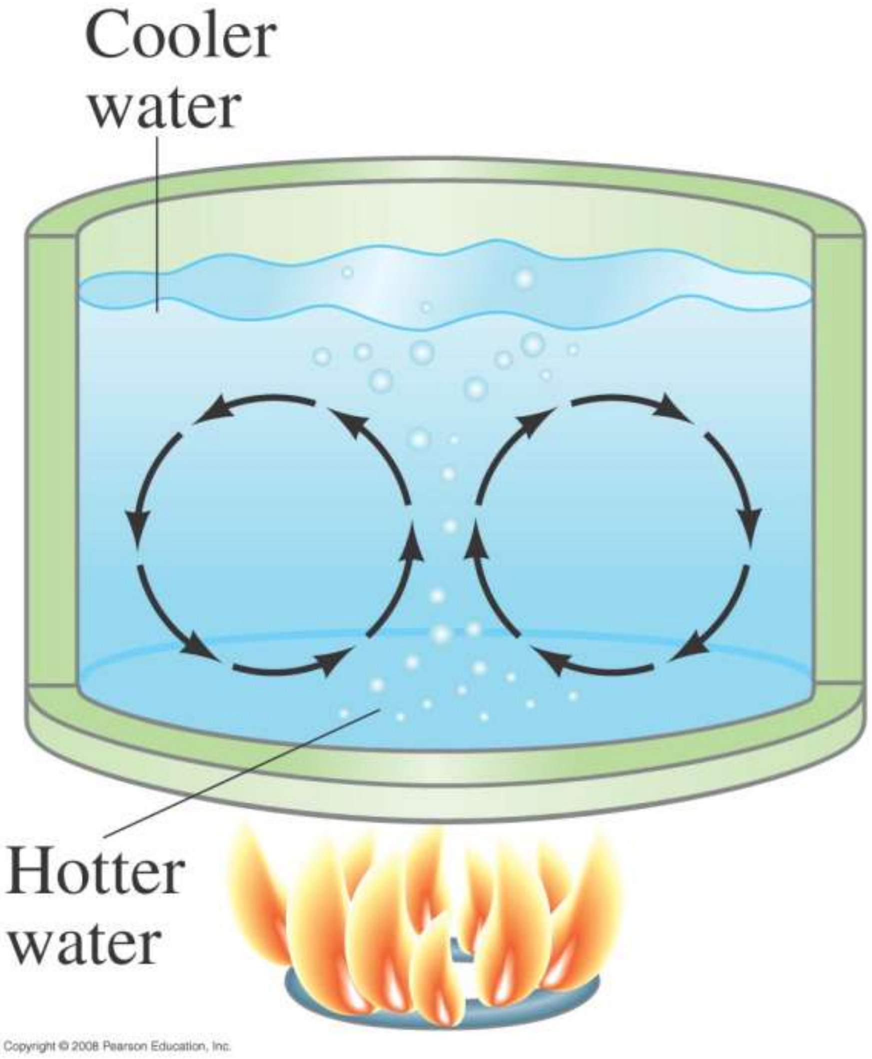
Same object (mass and material), low T feels cooler because heat loss $\Delta Q/\Delta t$ is greater.



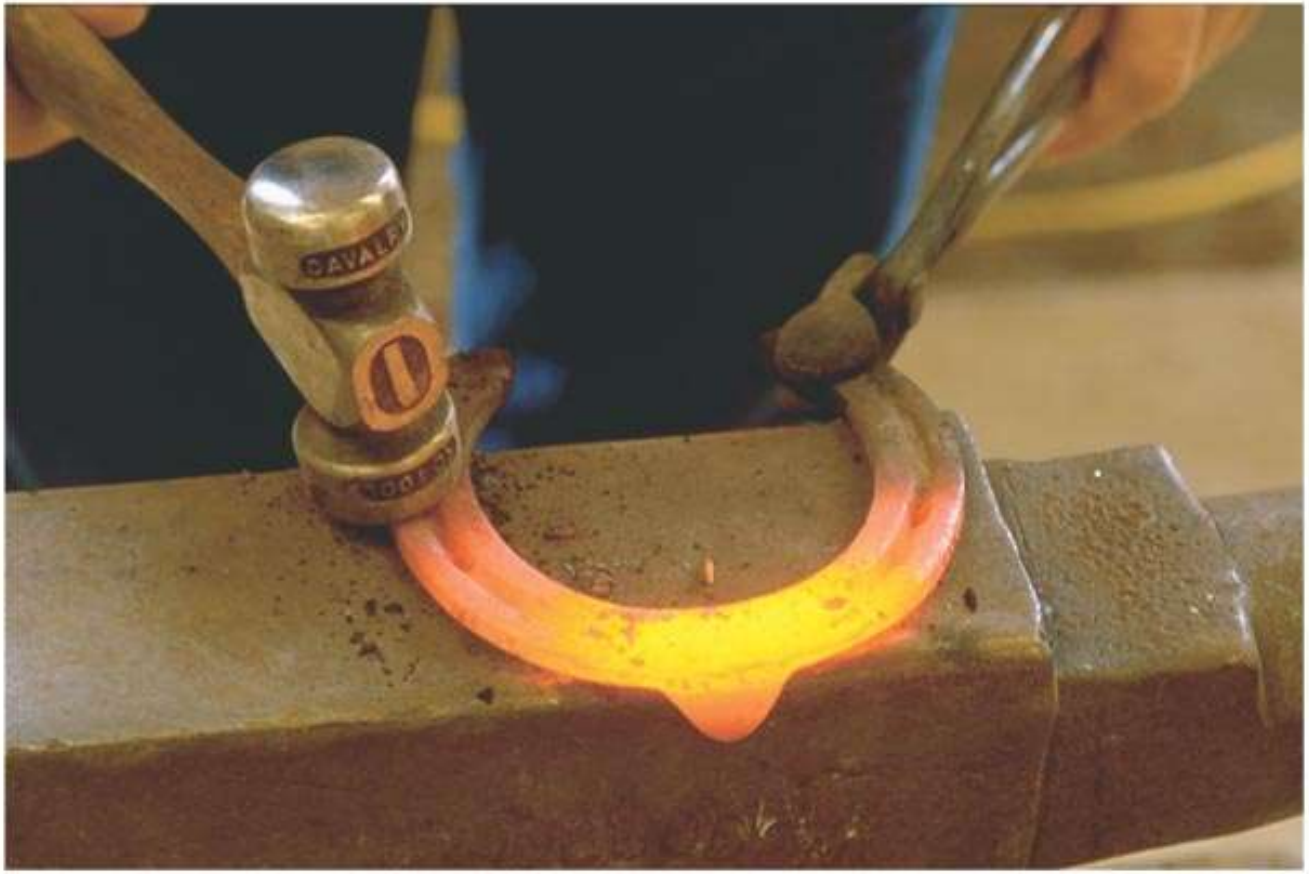
Different object of same mass and temp but greater κ feels cooler because heat loss $\Delta Q/\Delta t$ is greater.

Heat Transfer by Convection

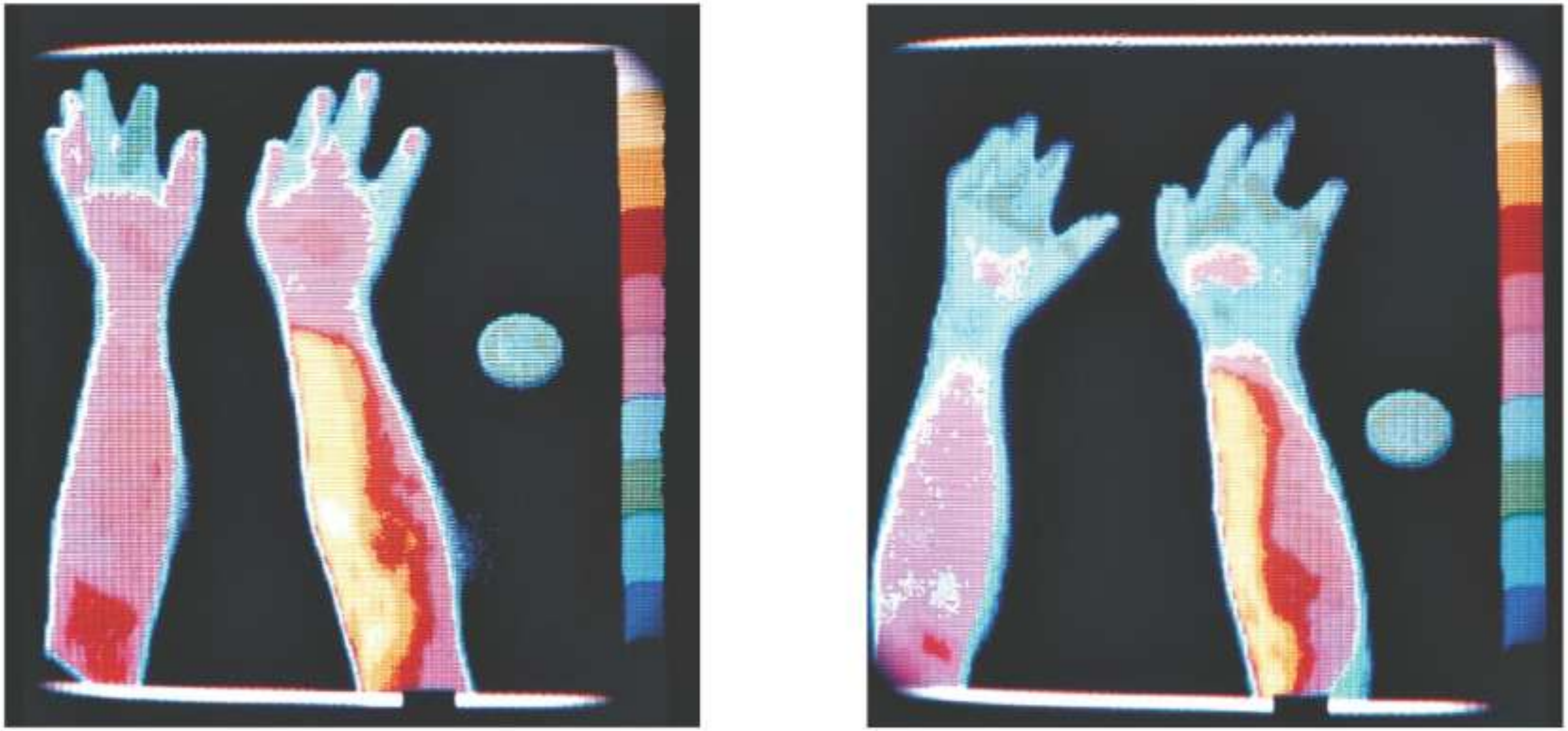
- Heat a fluid, it expands, $\rho\downarrow$
- Hot less dense fluid rises, cold dense fluid sinks
- Convection currents distribute heat
- Complex to describe mathematically



Heat Transfer by Radiation



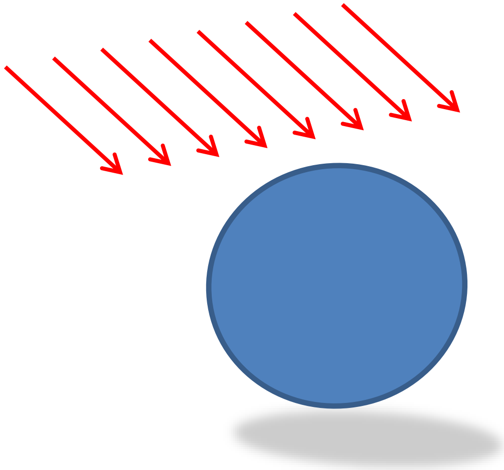
Objects with T > 0 emit light radiation (energy). If T is large light is visible.



(a) (b)

Cool objects emit non-visible infrared (IR) light radiation (energy).

Blackbodies



Light radiation (energy) falls on an object.

Some energy absorbed.
Some energy reflected* if shiny.
Some energy transmitted if transparent.

$E_{in} = E_{absorbed} + E_{reflected} + E_{transmitted}$ by CofE

*An object appears blue if it reflects blue but absorbs other colours.

A perfect blackbody would only absorb incident light.

As energy is absorbed, T rises.

But bodies with $T > 0$ emit radiation.

Equilibrium T reached when $P_{absorbed} = P_{emitted}$

At Low T emit IR, object appears black

At high T emit visible and appear bright

Sun is a hot blackbody!

If you plot light intensity versus wavelength get characteristic curves

Total power emitted obeys $P = \sigma A T_{skin}^4$

$\sigma = 5.6703 \times 10^{-8}$ W/m^2K^4

Real object similar

$$P = \varepsilon \sigma A T_{skin}^4$$

ε = emmissivity

ε = 1 for blackbody

ε = 0.95 for humans

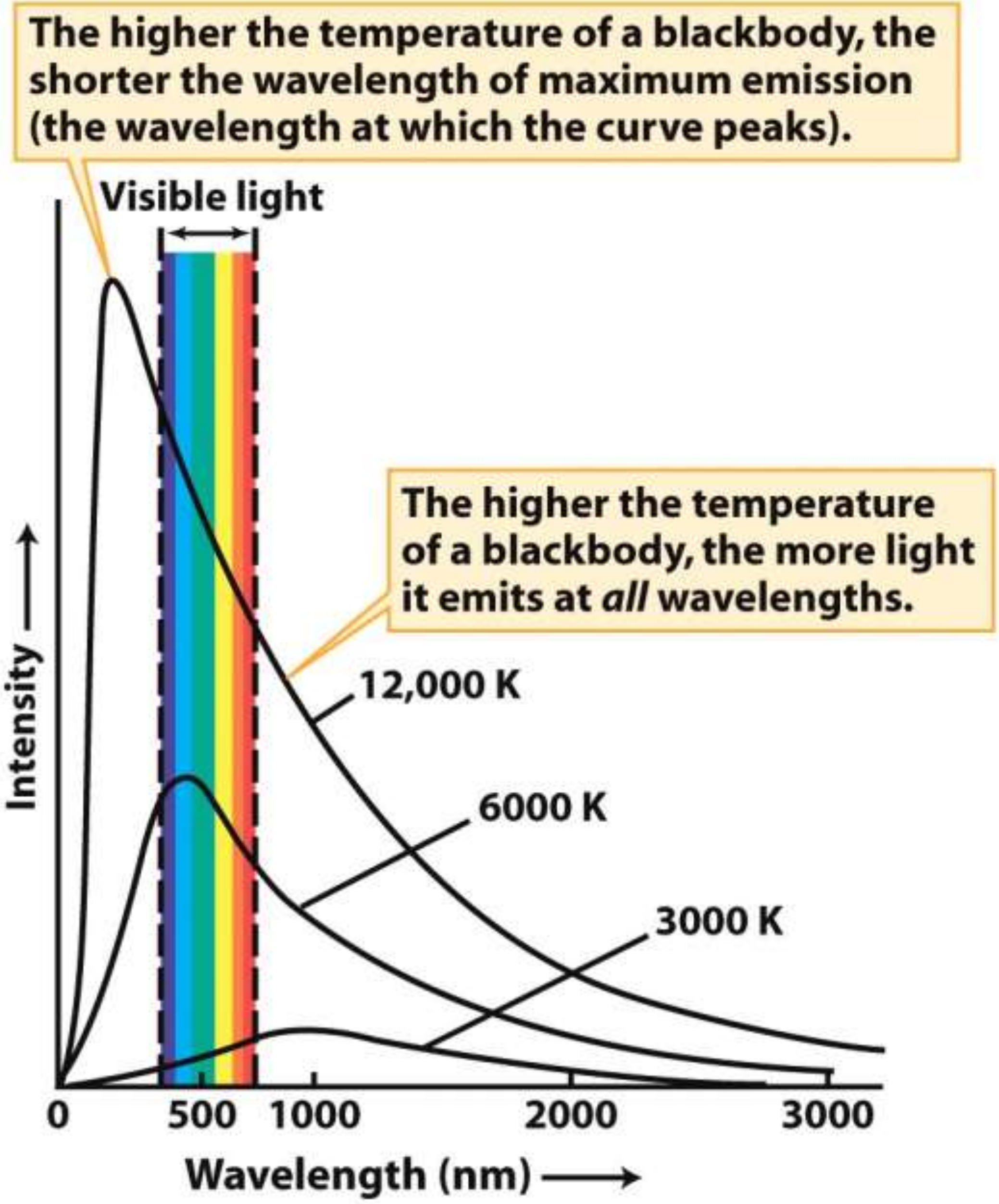
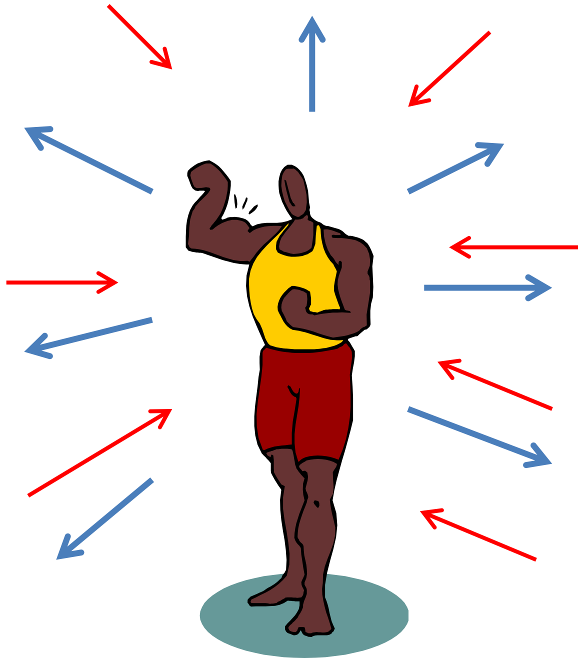


Figure 3-40
***Discovering the Essential Universe*, Fourth Edition**

- Human generate own internal heat from food consumption and radiate through skin
- Will absorb radiation through skin from surroundings.
- $P_{net} = P_{emit} - P_{absorb}$

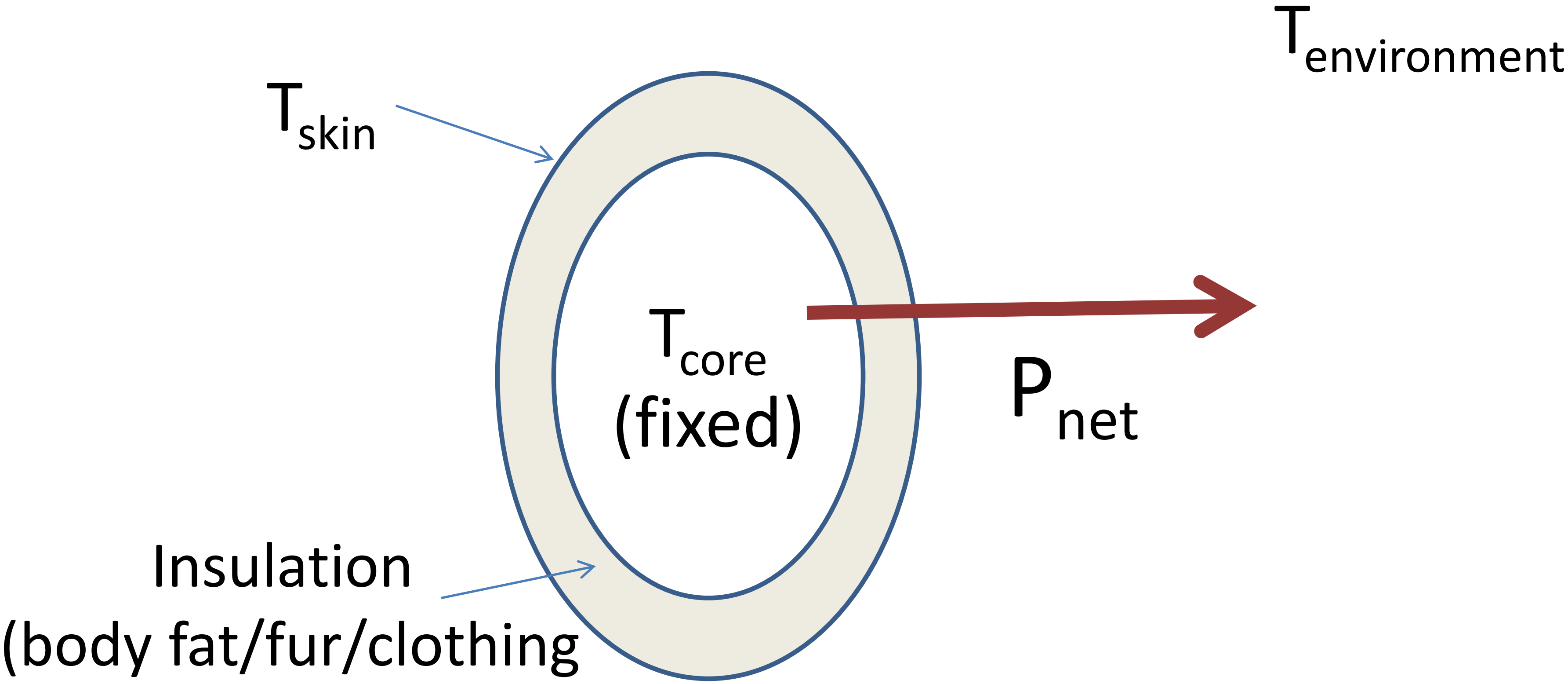


$$P_{net} = \varepsilon\sigma A T_{skin}^4 - \varepsilon\sigma A T_{env}^4$$

$$P_{net} = \varepsilon\sigma A\left(T_{skin}^4 - T_{env}^4\right)$$

How clothing works

- Heat conducts from skin to exterior of clothing.
- Energy then radiates away (and is absorbed) at the lower clothing temperature.
- E is conserved, so
- $P_{\text{conduction}} = P_{\text{net radiation}}$
- This determines T_{clothing} but is not simple to solve.



$T_{environment}$

T_{skin}

T_{core}
(fixed)

P_{net}

Insulation
(body fat/fur/clothing

Heat conducts thru insulation. If $T_{skin} > T_{env}$, heat radiates away.

$$P_{net} = \frac{\kappa A}{L}(T_{core} - T_{skin}) = \epsilon \sigma A\left(T_{skin}^4 - T_{env}^4\right)$$

How do fans/breezes cool?

If the fan blow air at room temperature towards you, why do you feel cooler than just standing in still air of same Temp?

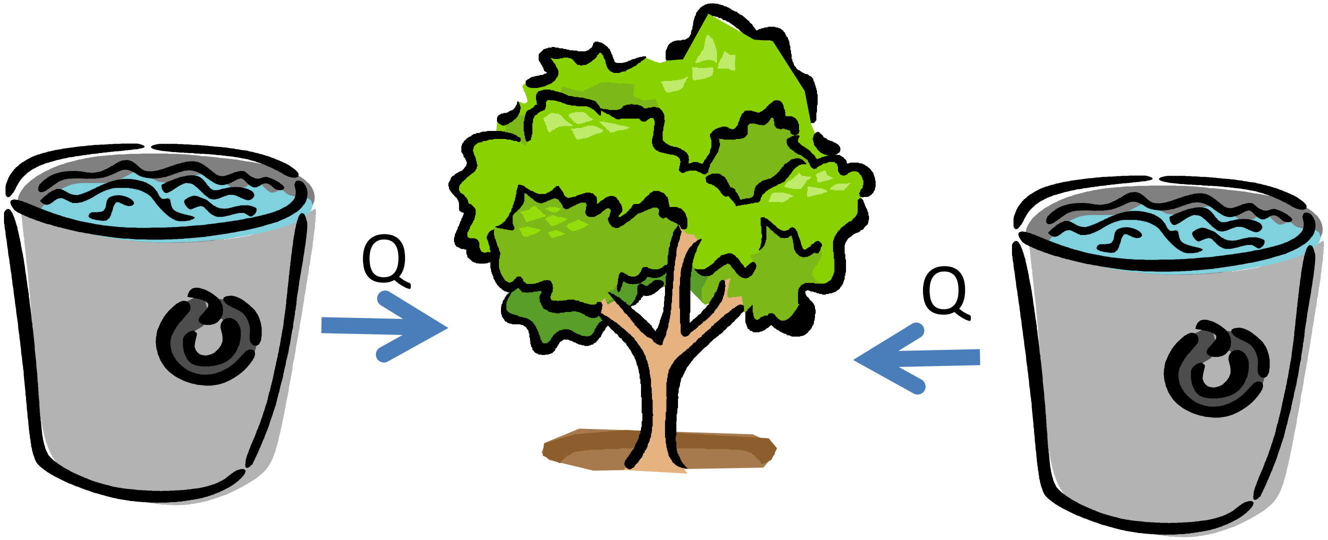
- Besides radiation, heat conducts away through air.
- It is a poor thermal conductor, so a shell of warm air builds up around you. So most heat lost is through radiation.
- But if the warm air is blown away, ΔT increases , and so conduction loss is much greater.

Climatic Effects

- Large bodies of water moderate local climate
- For water to cool or freeze, it must lose $Q = mc\Delta T$ or $Q = mL_F$. C and L_F are huge.
- That Q warms nearby land and air. T drop not as great as inland

Neat Trick

- Gardiners put pails of water near delicate plants
- Q from cooling water warms local environment
- Prevents frost damage



Convection plays a Part

- During day, land warms faster than water.
- Lands warms air above it, hot air rises
- Cool air from water flows in
- Onshore breeze
- At night, land and air above cools faster than air over water.
- Offshore breeze.