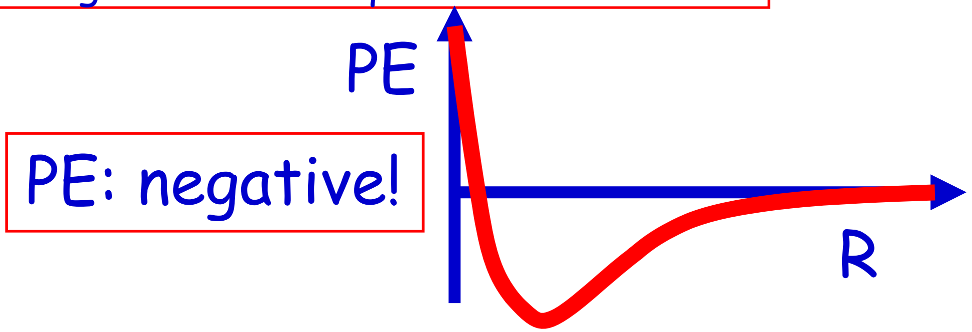
Internal energy

The internal (total) energy for an ideal gas is the total kinetic energy of the atoms/particles in a gas.

For a non-ideal gas: the internal energy is due to kinetic and potential energy associated with:

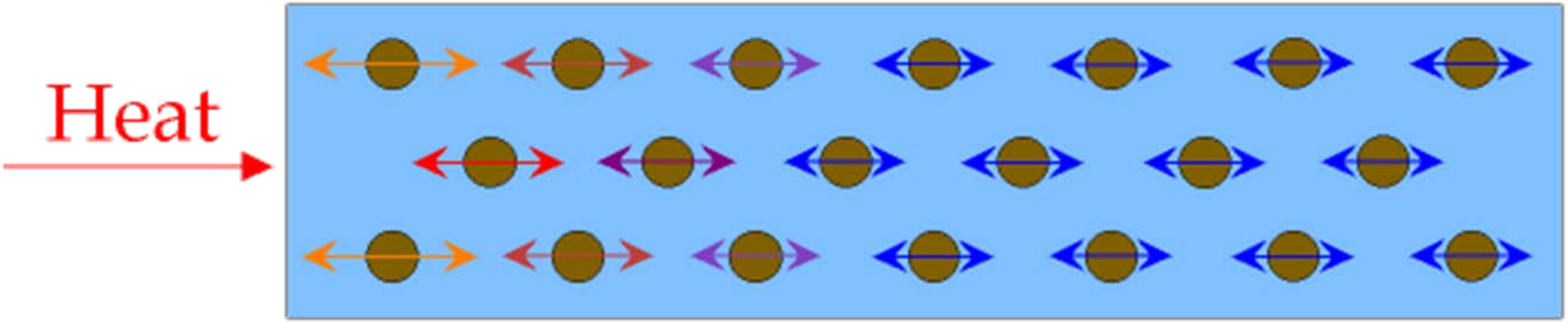
- translational motion
- rotational motion
- vibrational motion
- intermolecular potential energy

$$|PE_{\text{ideal gas}}=0| < |PE_{\text{non-ideal gas}}| < |PE_{\text{liquid}}| < |PE_{\text{solid}}|$$


PE: negative!

Heat

Heat: The transfer of energy between objects because their temperatures are different.



Heat: energy transfer   Symbol: Q

Units: Calorie (cal)   or   Joule (J)

1 cal = 4.186 J   (energy needed to raise 1 g of water by 1 ^{0}C)

Heat transfer to an object

The amount of energy transfer Q to an object with mass m when its temperature is raised by ΔT:

$$Q = cm\Delta T$$

Energy transfer
(J or cal)

Specific heat
(J/(kg °C) or cal/(g °C)

Mass of object

Change in
temperature

Example

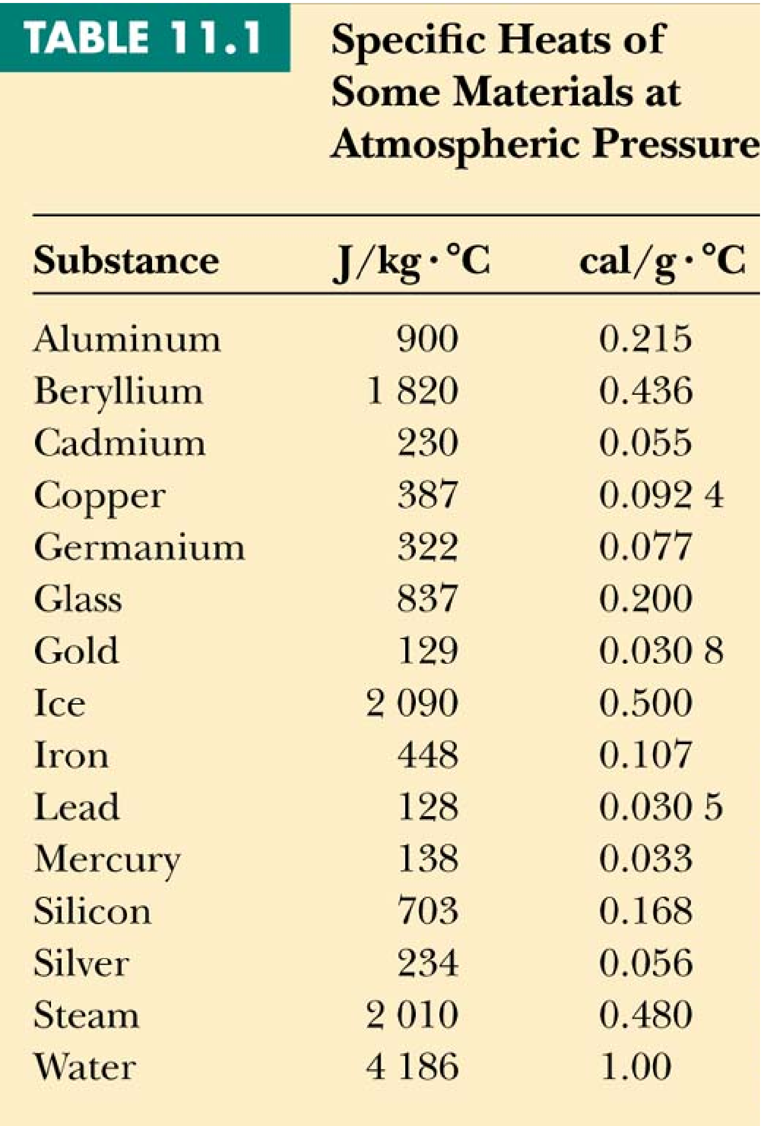


TABLE 11.1 Specific Heats of Some Materials at Atmospheric Pressure

Substance	J/kg·°C	cal/g·°C
Aluminum	900	0.215
Beryllium	1 820	0.436
Cadmium	230	0.055
Copper	387	0.092 4
Germanium	322	0.077
Glass	837	0.200
Gold	129	0.030 8
Ice	2 090	0.500
Iron	448	0.107
Lead	128	0.030 5
Mercury	138	0.033
Silicon	703	0.168
Silver	234	0.056
Steam	2 010	0.480
Water	4 186	1.00

A 1 kg block of Copper is raised in temperature by 10 ^{o}C. What was the heat transfer Q.?

Answer:

$Q=cm\Delta T$

$=387*1*10=3870$ J

1 cal = 4.186 J

Q=924.5 cal

Another one

A block of Copper is dropped from a height of 10 m. Assuming that all the potential energy is transferred into internal energy (heat) when it hits the ground, what is the raise in temperature of the block (c_{copper}=387 J/(kg °C))?

Potential energy: mgh=10 mg J

All transferred into heat Q: $Q = cm\Delta T$

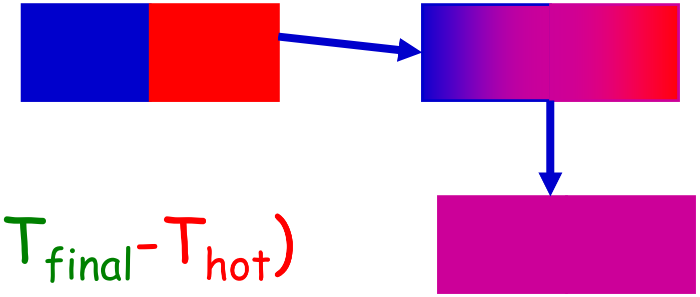
$10mg = 387m\Delta T$

$\Delta T = 10\,g/387 = 0.25\ ^{o}C$

Calorimetry

If we connect two objects with different temperature energy will transferred from the hotter to the cooler one until their temperatures are the same.

If the system is isolated:



$$Q_{cold}=-Q_{hot}$$

$$m_{cold}c_{cold}(T_{final}-T_{cold})=-m_{hot}c_{hot}(T_{final}-T_{hot})$$

the final temperature is: $T_{final}=\dfrac{m_{cold}c_{cold}T_{cold}+m_{hot}c_{hot}T_{hot}}{m_{cold}c_{cold}+m_{hot}c_{hot}}$

An example

The contents of a can of soda (0.33 kg) which is cooled to 4 °C is poured into a glass (0.1 kg) that is at room temperature (20 °C). What will the temperature of the filled glass be after it has reached full equilibrium (glass and liquid have the same temperature)?

Given c_{water}=4186 J/(kg °C) and c_{glass}=837 J/(kg °C)

$$Q_{cold}=-Q_{hot}$$

$$m_{water}c_{water}(T_{final}-T_{water})=-m_{glass}c_{glass}(T_{final}-T_{glass})$$

$$T_{final}=\frac{m_{water}c_{water}T_{water}+m_{glass}c_{glass}T_{glass}}{m_{water}c_{water}+m_{glass}c_{glass}}$$

= (0.33*4186*4+0.1*837*20)/(0.33*4186+0.1*837)=

= 4.9 °C

And another

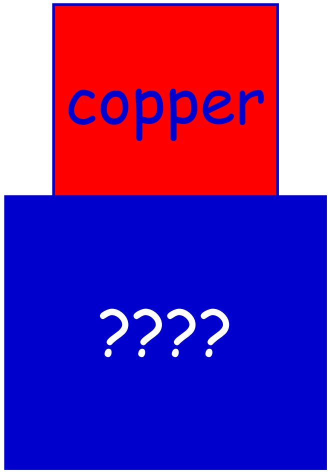
A block of unknown substance with a mass of 8 kg, initially at T=280 K is thermally connect to a block of copper (5 kg) that is at T=320 K (c_{copper}=0.093 cal/g ^{0}C). After the system has reached thermal equilibrium the temperature T equals 290 K. What is the specific heat of the unknown material in cal/g °C?

$$Q_{cold}=-Q_{hot}$$

$$m_{unknown}c_{unknown}(T_{final}-T_{unknown})=-m_{copper}c_{copper}(T_{final}-T_{copper})$$

$$c_{unknown}=\frac{-m_{copper}c_{copper}(T_{final}-T_{copper})}{m_{unknown}(T_{final}-T_{unknown})}$$

$$c_{unkown}=\frac{-5000\cdot 0.093\cdot(290-320)}{8000\cdot(290-280)}=0.17\ \text{cal/g}\ {}^{o}\text{C}$$



Heating water with a ball of Lead

A ball of Lead at T=100 °C with mass 300 g is dropped in a glass of water (0.3 L) at T=20 °C. What is the final (after thermal equilibrium has occurred) temperature of the system? (c_{water}=1 cal/g °C, c_{lead}=0.03 cal/g °C $\rho_{water}=10^3$ kg/m^3)

$$Q_{cold}=-Q_{hot}$$

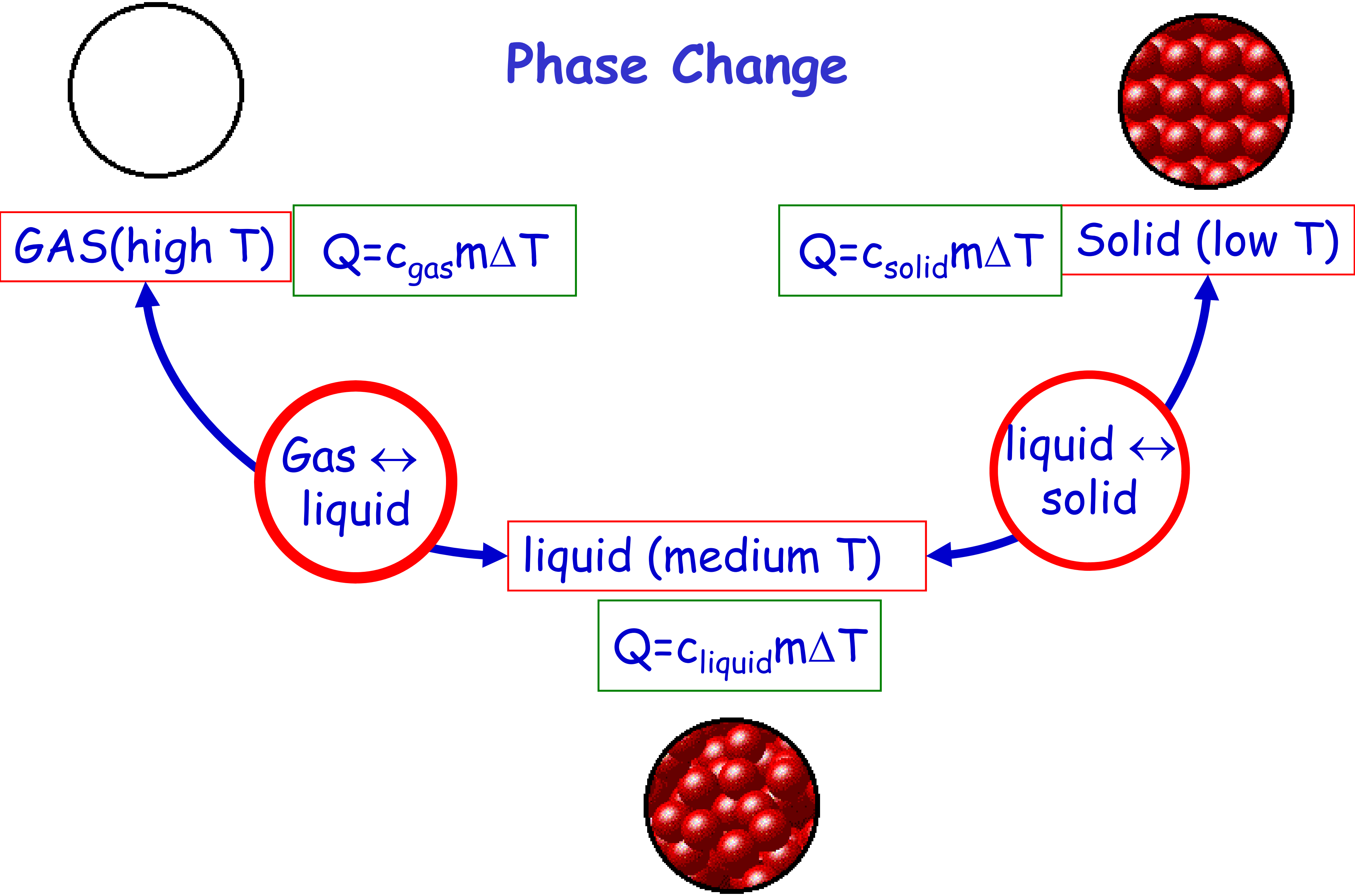
$$m_{water}c_{water}(T_{final}-T_{water})=-m_{lead}c_{lead}(T_{final}-T_{lead})$$

$$T_{final}=\frac{m_{water}c_{water}T_{water}+m_{lead}c_{lead}T_{lead}}{m_{water}c_{water}+m_{lead}c_{lead}}$$

$$= (0.3*1*20+0.3*0.03*100)/(0.3*1+0.3*0.03)=$$

$$= 6.9/0.309=22.3^{o}C$$

Phase Change



GAS(high T)

$Q=c_{gas}m\Delta T$

$Q=c_{solid}m\Delta T$

Solid (low T)

Gas ↔ liquid

liquid ↔ solid

liquid (medium T)

$Q=c_{liquid}m\Delta T$

Gas ↔ liquid

Phase change

When heat is added to a liquid, potential energy goes to 0 (the energy stored in the stickiness of the liquid is taken away)

DURING THE CHANGE FROM LIQUID TO GAS, THE KINETIC ENERGY DOES NOT CHANGE AND SO THE TEMPERATURE DOES NOT CHANGE.

ALL ADDED HEAT GOES TO CHANGING PE

When heat is taken from a gas, potential energy goes to the stickiness of the fluid

DURING THE CHANGE FROM GAS TO LIQUID, THE KINETIC ENERGY DOES NOT CHANGE AND SO THE TEMPERATURE DOES NOT CHANGE.

ALL REMOVED HEAT GOES TO CHANGING PE

liquid↔
solid

Phase change

When heat is added to a solid to make a liquid, potential energy in the bonds between the atoms become smaller

DURING THE CHANGE FROM SOLID TO LIQUID, THE KINETIC ENERGY DOES NOT CHANGE AND SO THE TEMPERATURE DOES NOT CHANGE.

ALL ADDED HEAT GOES TO CHANGING PE

When heat is taken from a liquid, the bonds between atoms becomes stronger (potential energy is more negative)

DURING THE CHANGE FROM LIQUID TO SOLID, THE KINETIC ENERGY DOES NOT CHANGE AND SO THE TEMPERATURE DOES NOT CHANGE.

ALL REMOVED HEAT GOES TO CHANGING PE

Okay, the Temperature does not change in a phase transition!
But what is the amount of heat added to make the phase transition?

Gas ↔ liquid

$$Q_{gas\to liquid}=-ML_v$$

$$Q_{liquid\to gas}=+ML_v$$

M:mass

L_v=latent heat of vaporization (J/kg or cal/g) depends on material.

solid ↔ liquid

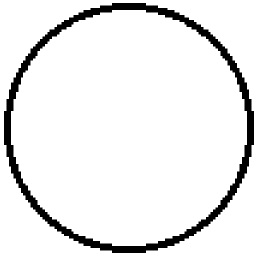
$$Q_{liquid\rightarrow solid} = -ML_f$$

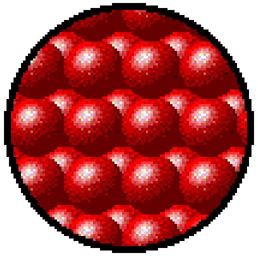
$$Q_{solid\rightarrow liquid} = +ML_f$$

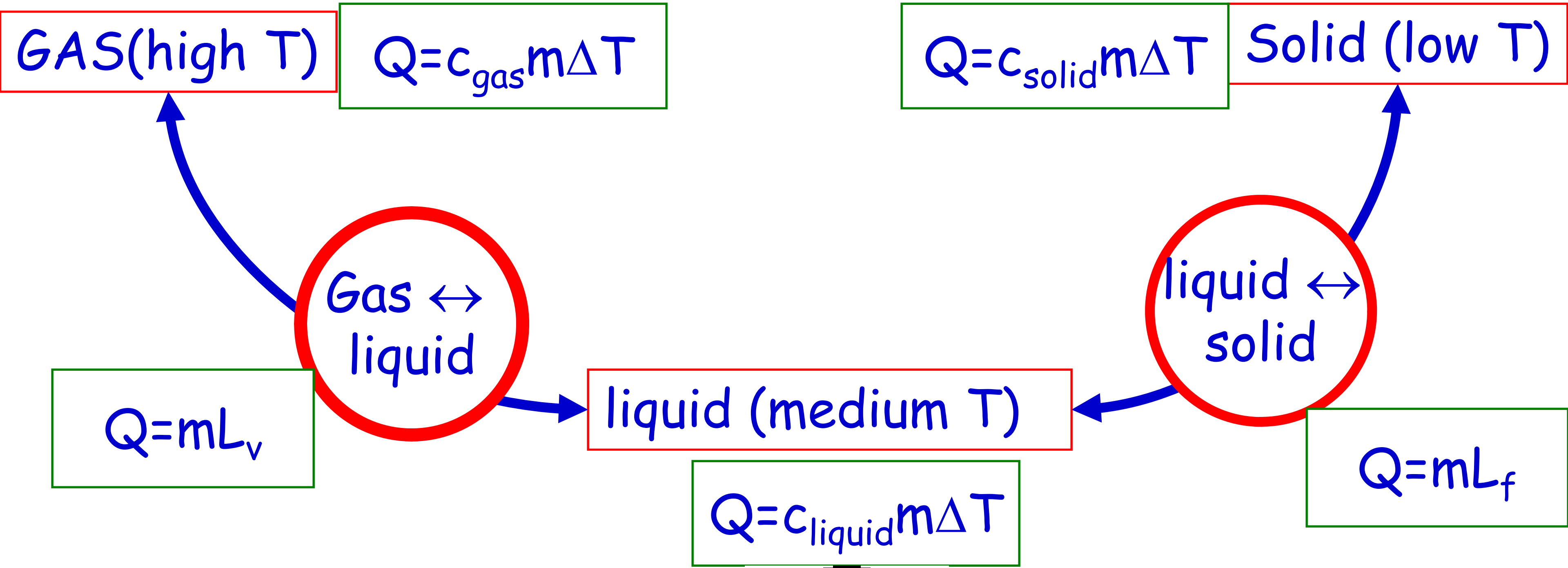
M:mass

L_f=latent heat of fusion (J/kg or cal/g) depends on material.

Phase Change







GAS(high T)

$Q=c_{gas}m\Delta T$

Solid (low T)

$Q=c_{solid}m\Delta T$

Gas ↔ liquid

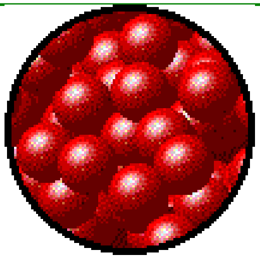
$Q=mL_v$

liquid ↔ solid

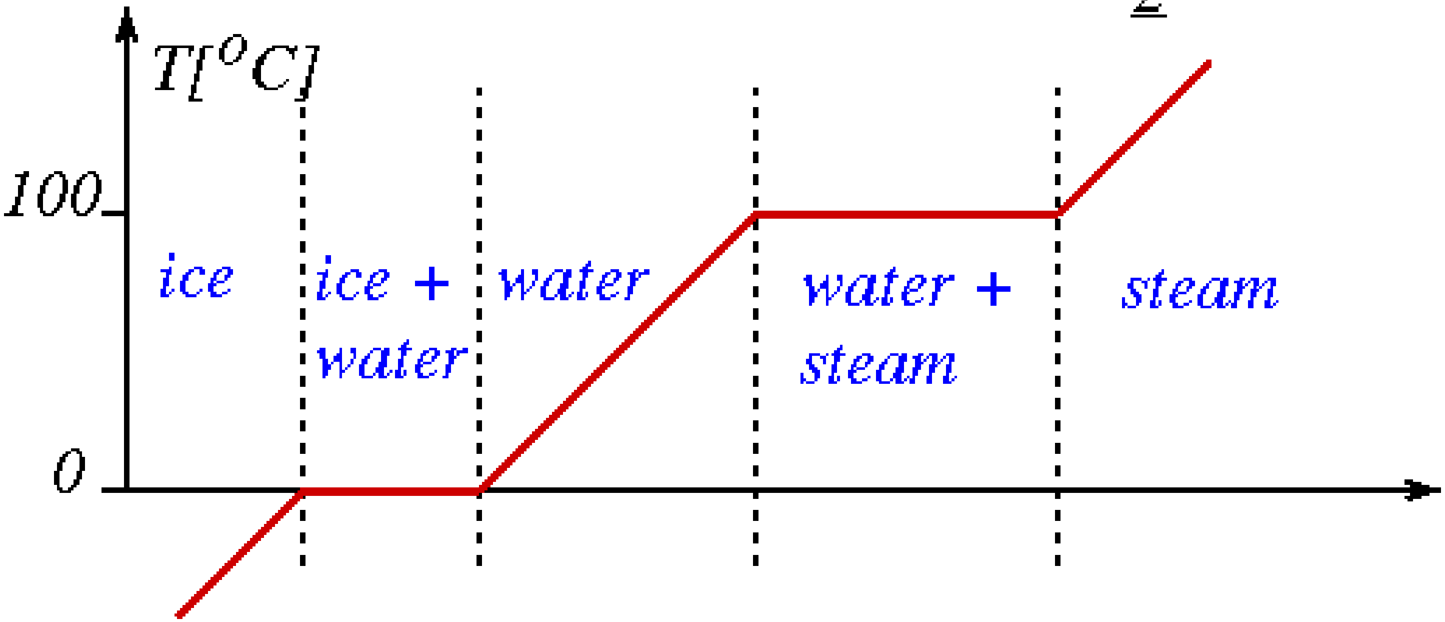
$Q=mL_f$

liquid (medium T)

$Q=c_{liquid}m\Delta T$

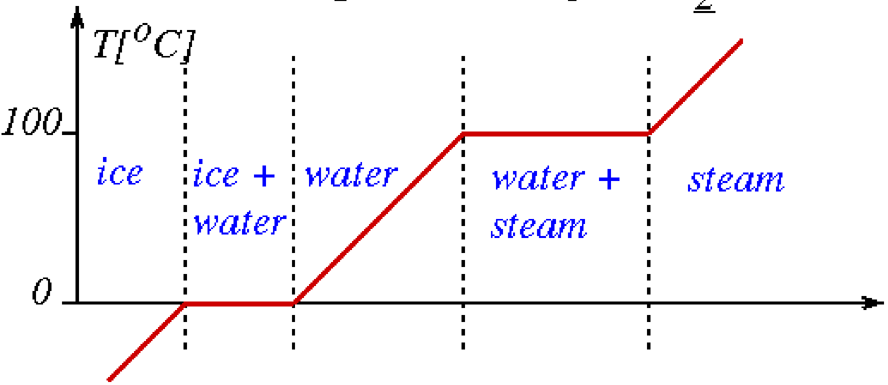


Example: Heating of H_2O



(a)	ice	$Q = m\, c_{ice} \Delta T$	raises T of ice
(b)	ice+water	$Q = m\, L_f$	melts ice
(c)	water	$Q = m\, c_{water} \Delta T$	raises T of water
(d)	water + steam	$Q = m\, L_v$	vaporizes water
(e)	steam	$Q = m\, c_{steam} \Delta T$	raises T of steam

Example: Heating of H_2O



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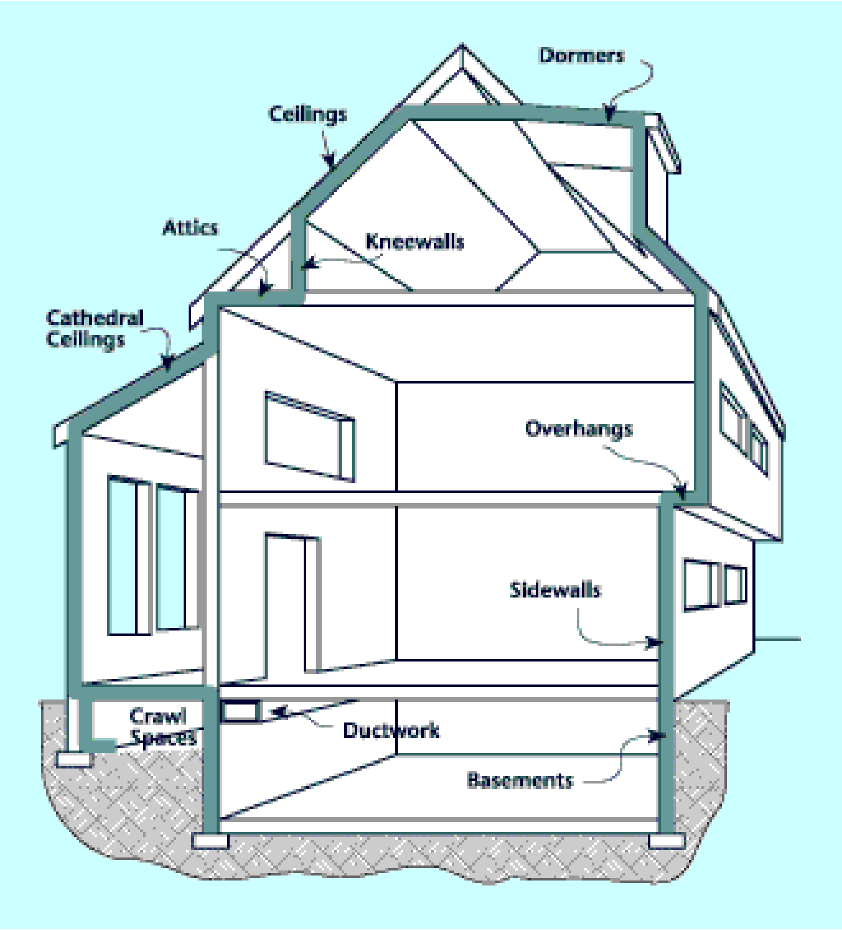
(b)	ice+water	$Q = m\, L_f$	melts ice
(c)	water	$Q = m\, c_{water} \Delta T$	raises T of water
(d)	water + steam	$Q = m\, L_v$	vaporizes water
(e)	steam	$Q = m\, c_{steam} \Delta T$	raises T of steam

Ice with T=-30 °C is heated to steam of T=150 °C.
How many heat (in cal) has been added in total?

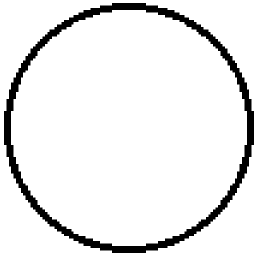
$c_{ice}=0.5$ cal/g °C
$c_{water}=1.0$ cal/g °C
$c_{steam}=0.480$ cal/g °C
$L_f=540$ cal/g
$L_v=79.7$ cal/g
m=1 kg=1000g

A) Ice from -30 to 0 °C	$Q=1000*0.5*30=$ 15000 cal
B) Ice to water	$Q=1000*540=$ 540000 cal
C) water from 0 °C to 100 °C	$Q=1000*1.0*100=$100000 cal
D) water to steam	$Q=1000*79.7=$ 79700 cal
E) steam from 100 °C to 150 °C	$Q=1000*0.48*50=$24000 cal
TOTAL	$Q=$ =758700 cal

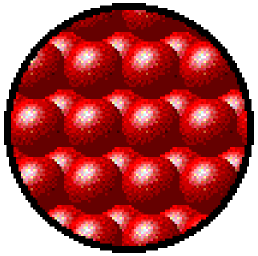
PHYSICS 111
Thermal conduction

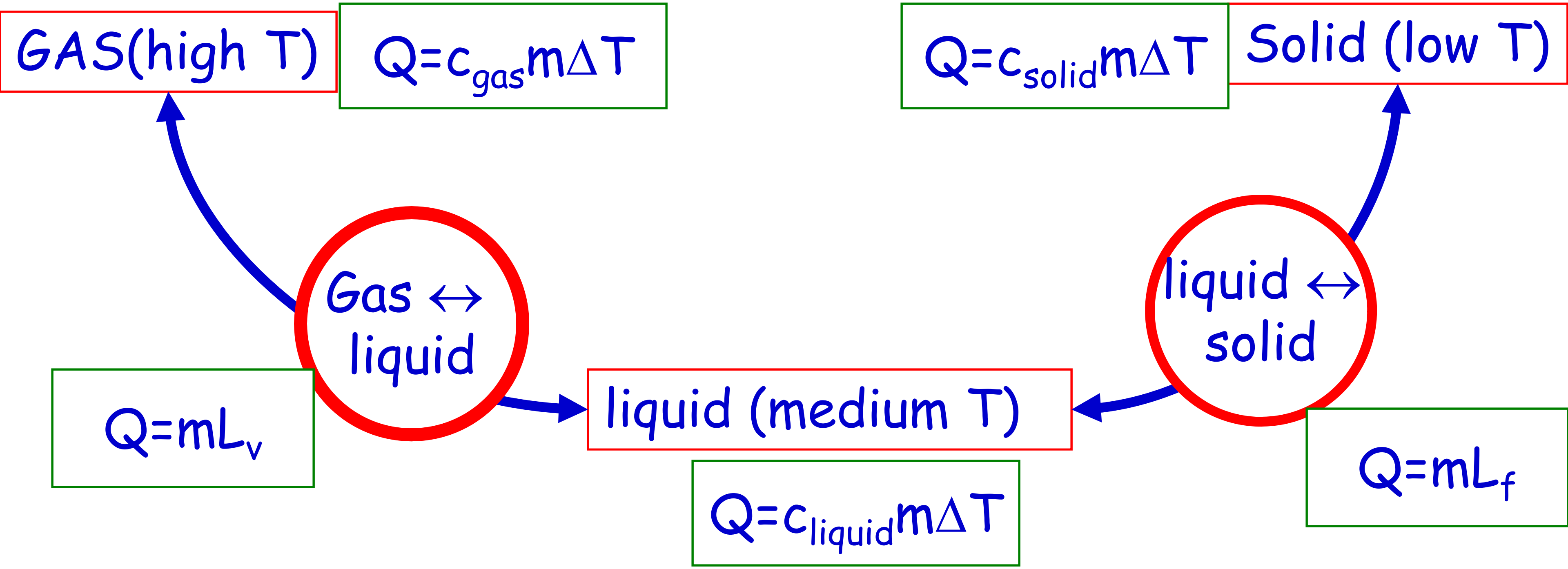


ISOLATION



Previously: Phase Change





GAS(high T)

$Q=c_{gas}m\Delta T$

$Q=c_{solid}m\Delta T$

Solid (low T)

Gas ↔ liquid

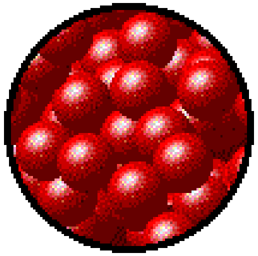
liquid ↔ solid

$Q=mL_v$

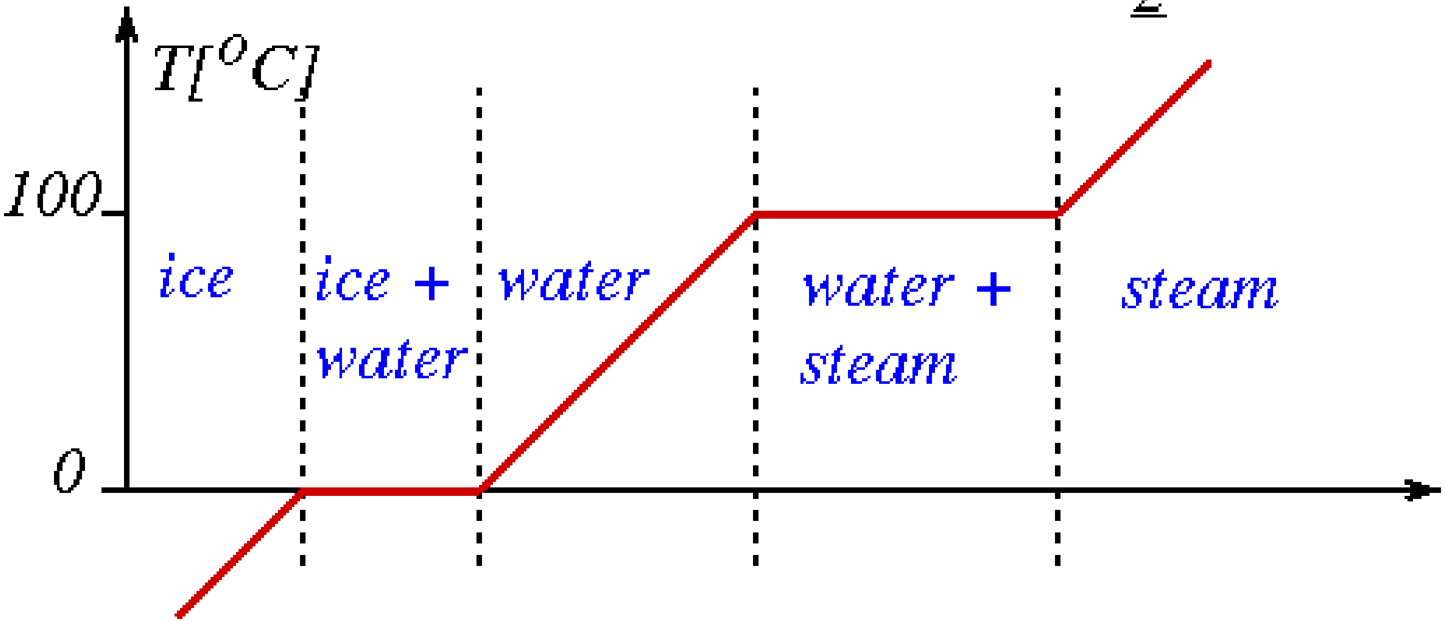
liquid (medium T)

$Q=c_{liquid}m\Delta T$

$Q=mL_f$



Example: Heating of H_2O



(a)	ice	$Q = m\, c_{ice} \Delta T$	raises T of ice
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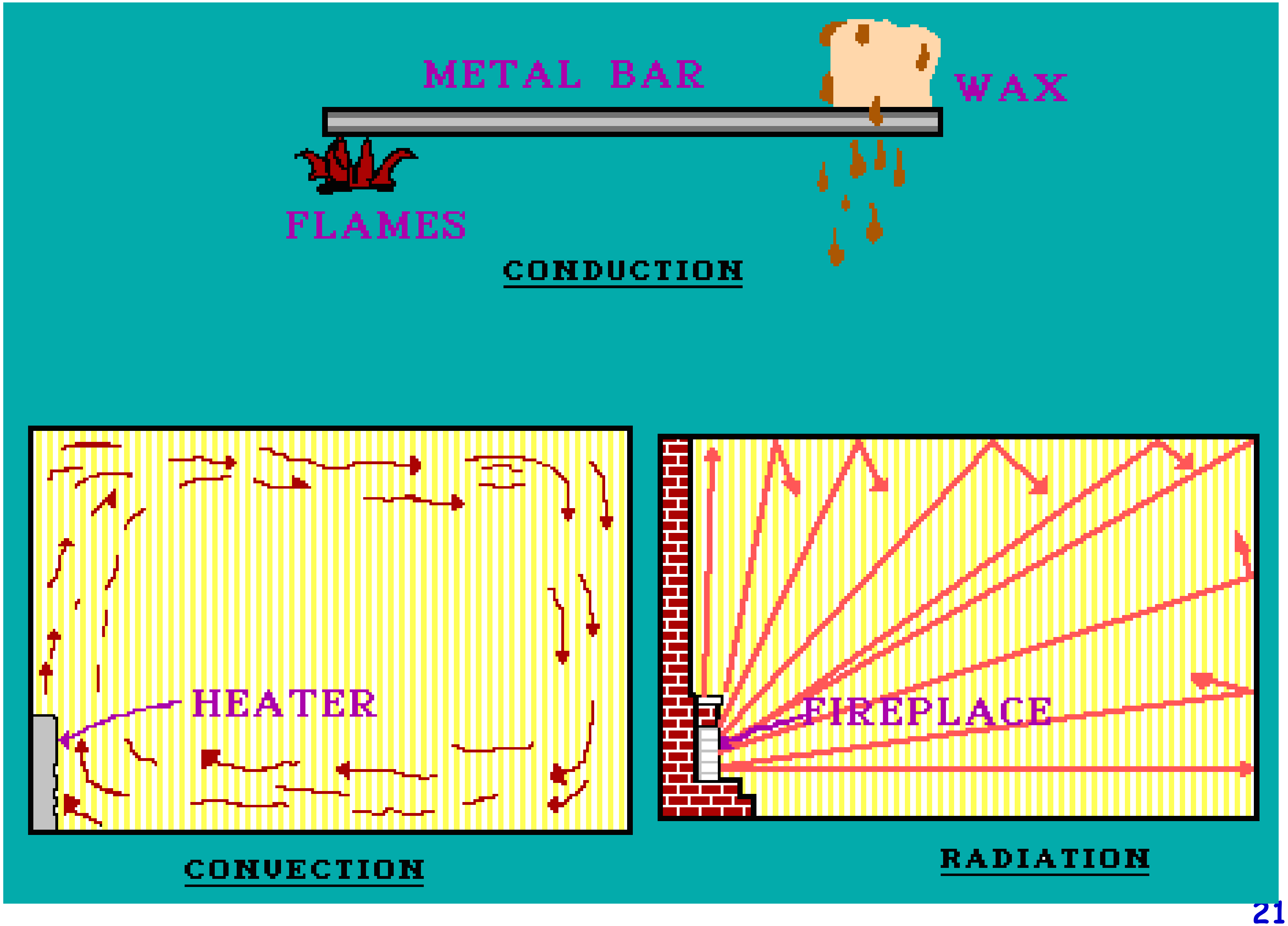
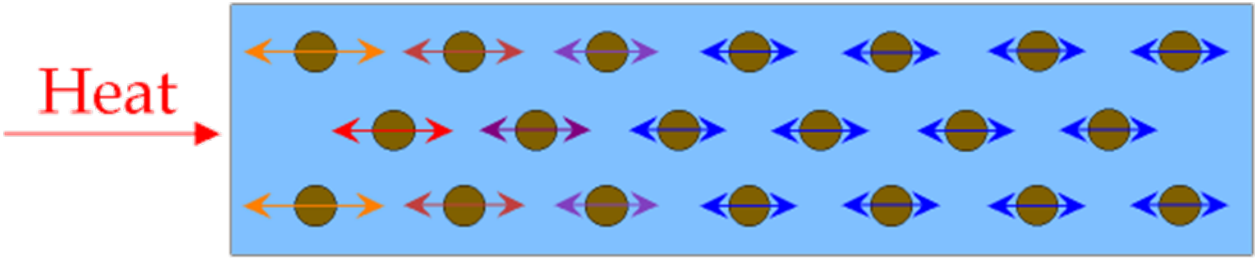
(d)	water + steam	$Q = m\, L_v$	vaporizes water
(e)	steam	$Q = m\, c_{steam} \Delta T$	raises T of steam

How can heat be transferred?



Conduction

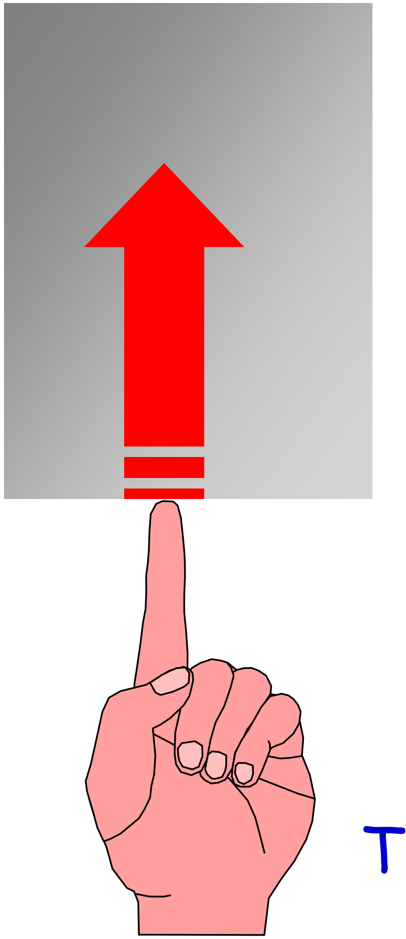


Touching different materials: Some feel cold, others feel warm, but all are at the same temperature…

Thermal conductivity

metal

$T=20\ ^0C$

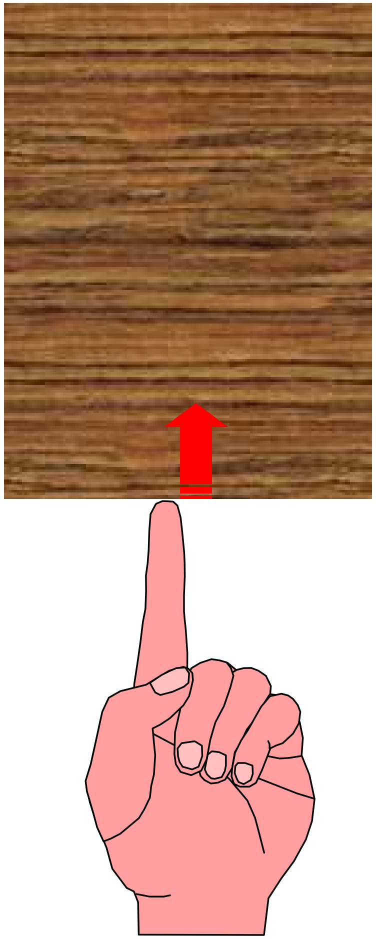


$T=37\ ^0C$

The heat transfer in the metal is much faster than in the wood: (thermal conductivity)

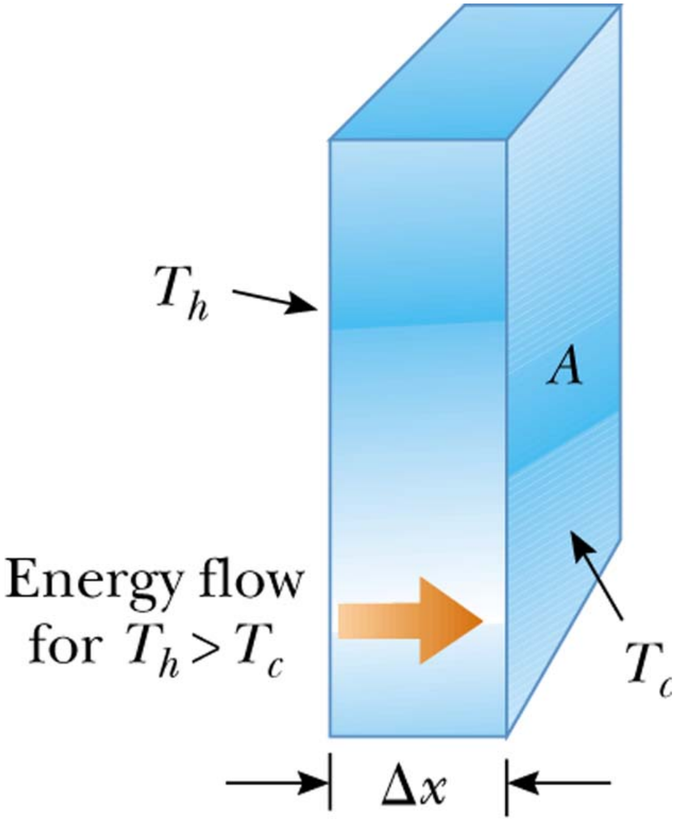
wood

$T=20\ ^0C$



$T=37\ ^0C$

Heat transfer via conduction



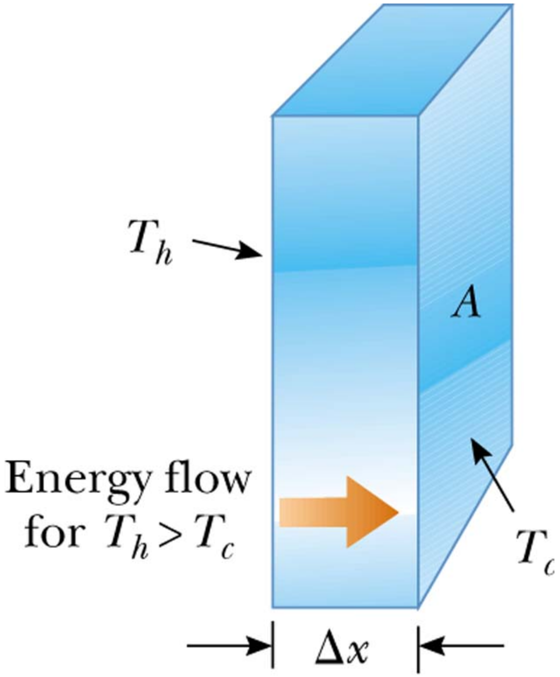
Conduction occurs if there is a temperature difference between two parts of a conducting medium

Rate of energy transfer P
$P = Q/\Delta t$ (unit Watt)
$P = kA(T_h - T_c)/\Delta x = kA\Delta T/\Delta x$

k: thermal conductivity
Unit: J/(m.s.°C)

metal k~300 J/(m.s.°C)
gases k~0.1 J/(m.s.°C)
nonmetals~1 J/(m.s.°C)

Example



A glass window ($A=4\ m^2$, $\Delta x=0.5\ cm$) separates a living room ($T=20\ ^0C$) from the outside ($T=0\ ^oC$). A) What is the rate of heat transfer through the window ($k_{glass}=0.84\ J/(m.s.^oC)$)? B) By what fraction does it change if the surface becomes 2x smaller and the temperature drops to $-20\ ^0C$?

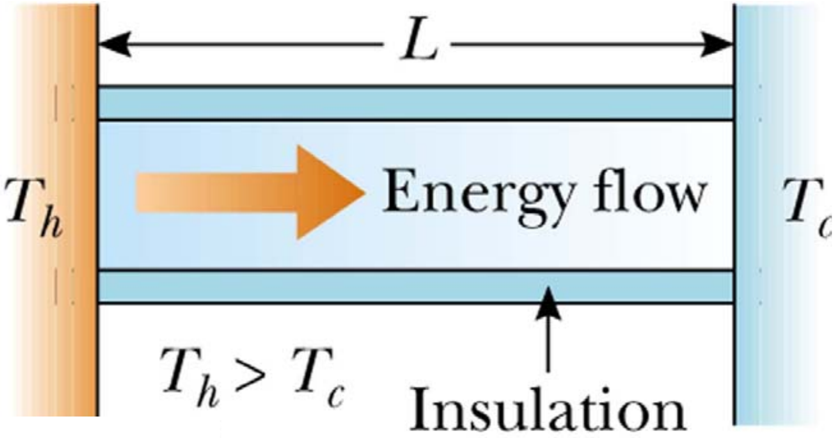
A) $P=kA\Delta T/\Delta x=0.84*4*20/0.005=13440$ Watt

B) $P_{orig}=kA\Delta T/\Delta x$ $P_{new}=k(0.5A)(2\Delta T)/\Delta x=P_{orig}$

The heat transfer is the same

Another one.

Heat reservoir



Heat sink

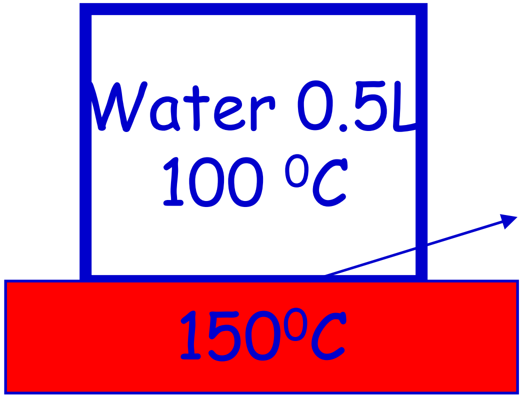
An insulated gold wire (i.e. no heat lost to the air) is at one end connected to a heat reservoir ($T=100\ ^0C$) and at the other end connected to a heat sink ($T=20\ ^0C$). If its length is 1m and P=200 W what is its cross section (A)?

$k_{gold}=314\ J/(m.s.^0C)$.

$P=kA\Delta T/\Delta x=314*A*80/1=25120*A=200$

$A=8.0E-03\ m^2$

And another



A=0.03 m^2 thickness: 0.5 cm.

A student working for his exam feels hungry and starts boiling water (0.5L) for some noodles. He leaves the kitchen when the water just boils. The stove's temperature is 150 ^0C. The pan's bottom has dimensions given above. Working hard on the exam, he only comes back after half an hour. Is there still water in the pan? (L_v=540 cal/g, k_{pan}=1 cal/(m.s.^0C)

To boil away 0.5L (=500 g) of water: $Q=L_v*500=270000$ cal

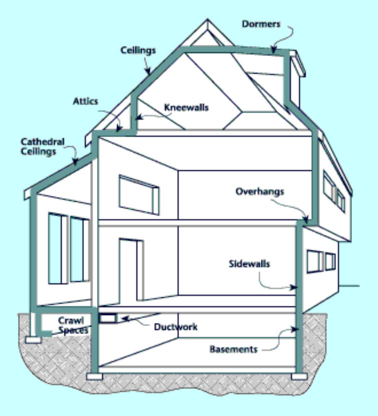
Heat added by the stove: $P=kA\Delta T/\Delta x=1*0.03*50/0.005=$

$=300$ cal

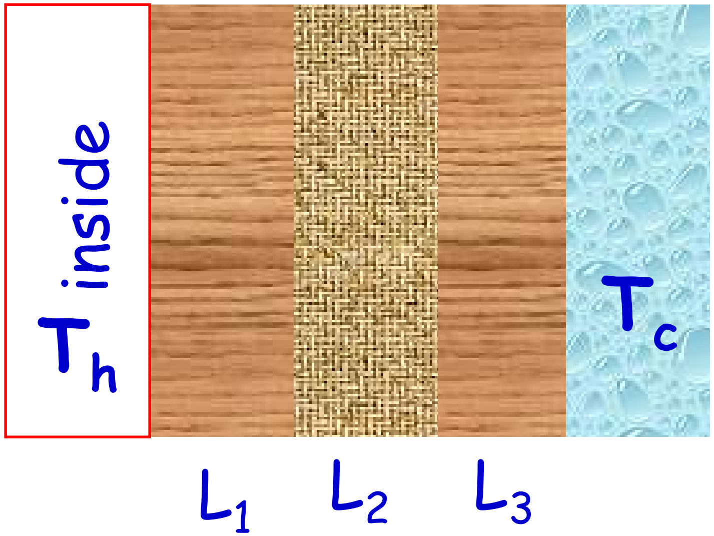
$P=Q/\Delta t$ $\Delta t=Q/P=270000/300=900$ s (15 minutes)

He'll be hungry for a bit longer…

Isolation



$$P = \frac{Q}{\Delta t} = \frac{A(T_h - T_c)}{\sum_i (L_i / k_i)}$$



A house is built with 10 cm thick wooden walls and roofs. The owner decides to install insulation. After installation the walls and roof are 4 cm wood+2 cm isolation+4 cm wood. If k_{wood}=0.10 J/(m.s.^{0}C) and $k_{isolation}$=0.02 J/(m.s.^{0}C), by what factor does he reduce his heating bill?

$P_{before}=A\Delta T/[0.10/0.10]=A\Delta T$

$P_{after}=A\Delta T/[0.04/0.10+0.02/0.02+0.04/0.10]=0.55A\Delta T$

Almost a factor of 2 (1.81)!