Chapter 19

Temperature, Heat, and the First Law of Thermodynamics

19-1 Thermodynamics

Thermodynamics

Study of thermal energy (internal energy) of systems

Temperature is the central concept of thermodynamics

19-1 Thermodynamics

Our “temperature sense” is not always reliable

Metal and wood may have the same temperature, but by touching, we think that metal is colder than wood

Metal removes energy form our fingers more quickly than wood does

19-1 Thermodynamics

Physicists measure temperature on the Kelvin scale

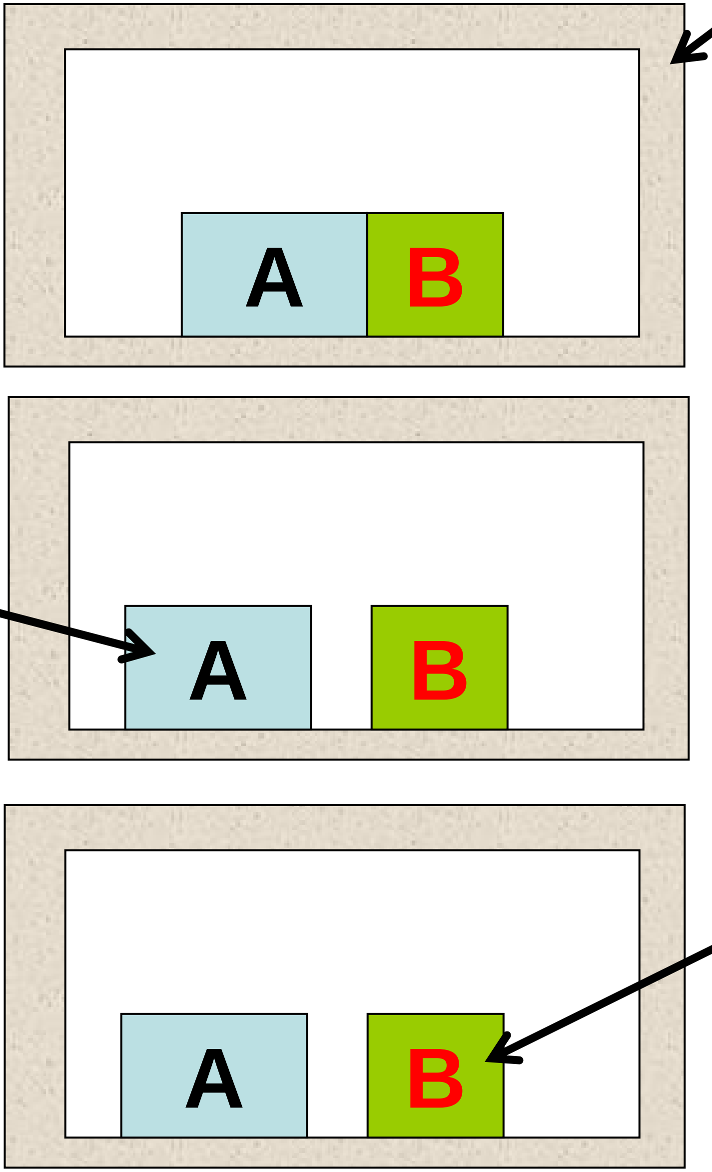
The lowest attainable temperature is zero on the Kelvin scale

19-2 The Zero Law of Thermodynamics

The zero law of thermodynamics

Every body has a property called temperature. When two bodies are in thermal equilibrium, their temperatures are equal. And vice versa

19-2 The Zero Law of Thermodynamics



insulator

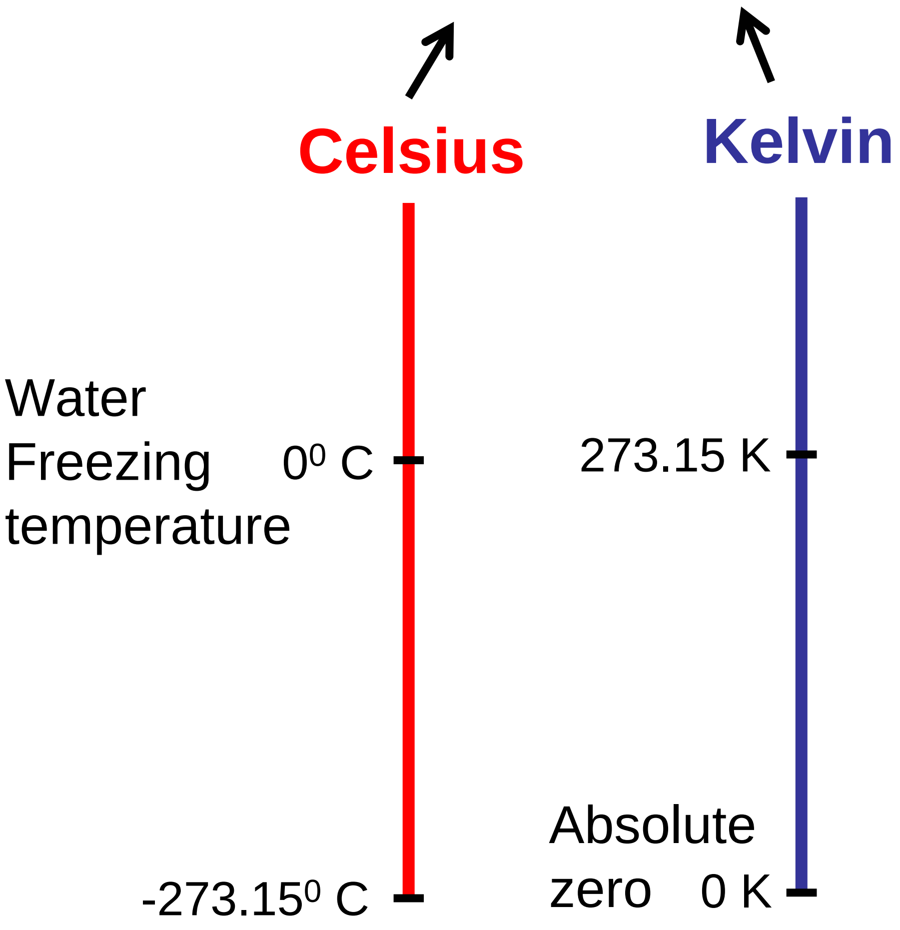
Long enough time to reach equilibrium

If temperature = 300 K

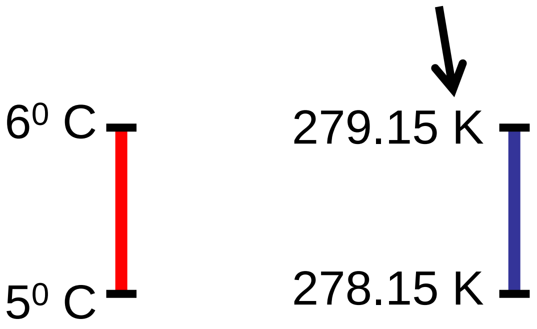
Temperature should be 300 K

19-4 The Celsius and Fahrenheit scales

$$T_c = T - 273.15^0$$



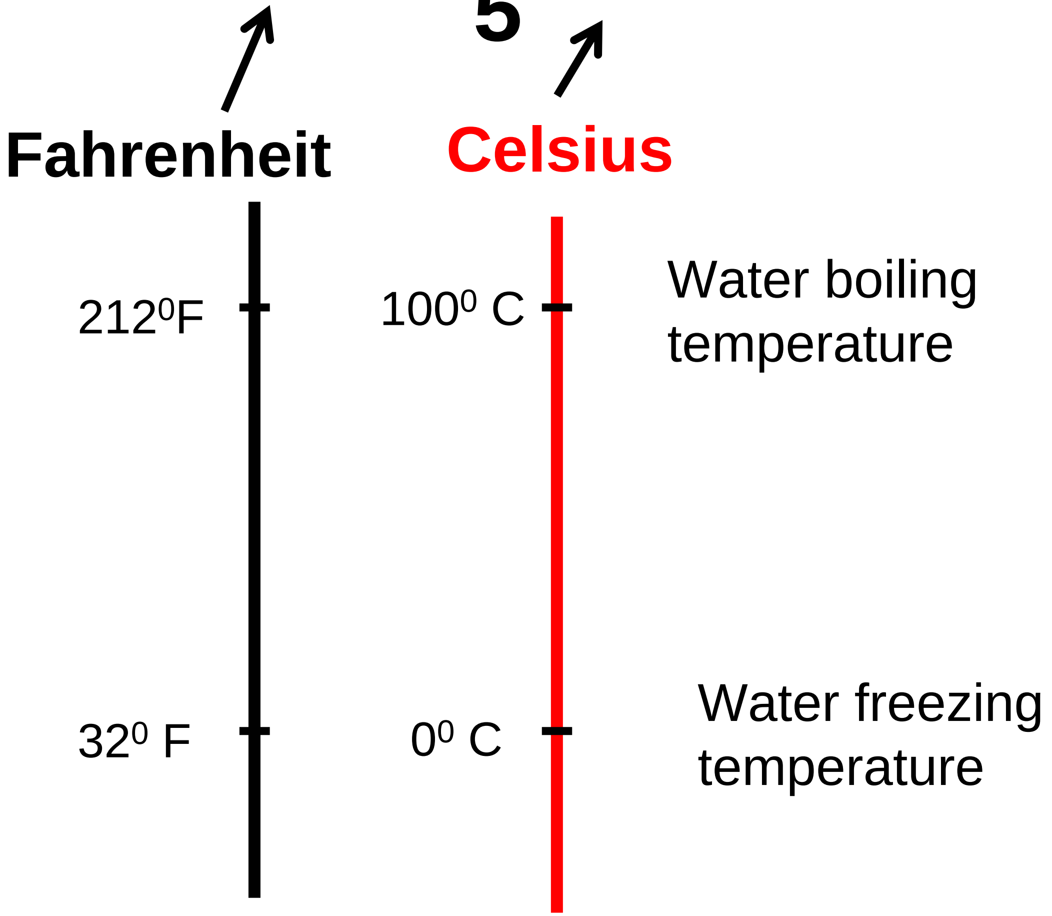
Note we do not use ^{0} for K



The Celsius degree has the same size as the Kelvin. However the zero of the Celsius scale is shifted to a more convenient value than absolute zero

19-4 The Celsius and Fahrenheit scales

$$T_F = \frac{9}{5} T_C + 32^0$$



Fahrenheit

Celsius

212^0F

100^0 C

Water boiling temperature

32^0 F

0^0 C

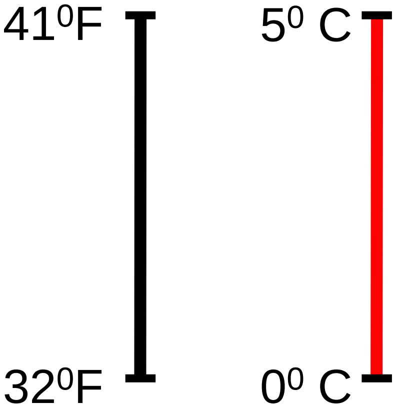
Water freezing temperature

19-4 The Celsius and Fahrenheit scales

$$T_F = \frac{9}{5} T_C + 32^0$$

Difference

The temperature difference of 5 Celsius degrees is equivalent to a temperature difference of 9 Fahrenheit degrees



$$5C^0 = 9F^0$$

Note ^{0} is after F to indicate difference

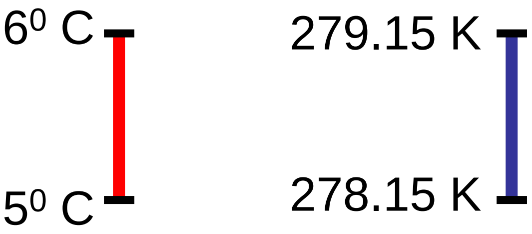
Equivalence

$$0^0C = 32^0F$$

Zero on Celsius scale is equivalent to 32 degrees on Fahrenheit scale

19-4 The Celsius and Fahrenheit scales

$$T_c = T - 273.15^0$$



6^0 C

5^0 C

279.15 K

278.15 K

Difference

$$1C^0 = 1K$$

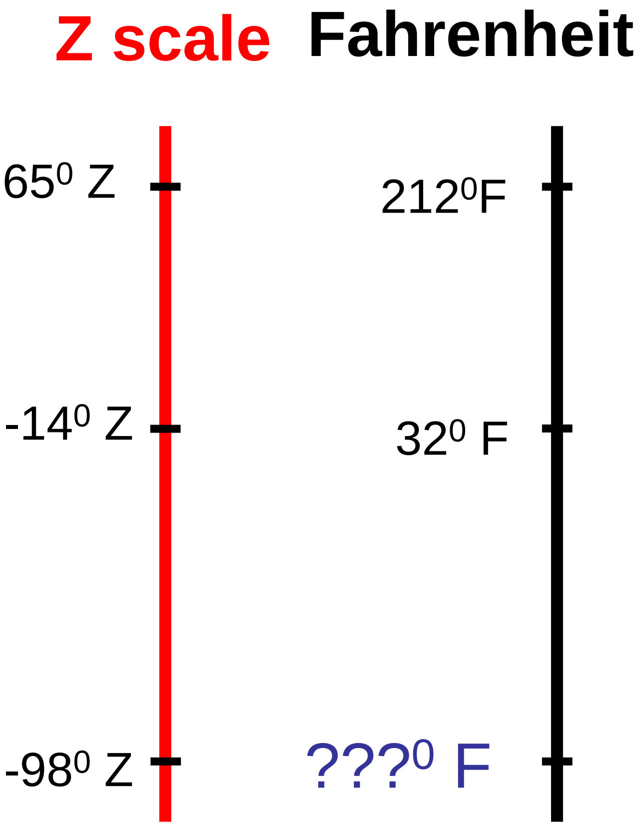
Note no ^{0} sign used

Equivalence

$$0^0C = 273.15K$$

19-4 The Celsius and Fahrenheit scales

Sample Problem 19-1



$$(65 - (-14))\, Z^0 = (212 - 32)\, F^0$$

$$Z^0 = \frac{212 - 32}{65 + 14}\, F^0 = \frac{180}{79}\, F^0$$

$$((-14) - (-98))\, Z^0 = 84\, Z^0$$

$$84\, Z^0 = 84\, \frac{180}{79}\, F^0 = 191\, F^0$$

$$???\ = 32 - 191 = -159^0\, F$$

19-4 The Celsius and Fahrenheit scales

Check point 1

19-4 The Celsius and Fahrenheit scales

Problem Solving Tactics

Do not confuse
a temperature
with
a temperature change or difference

$5^0C = 278.15K$

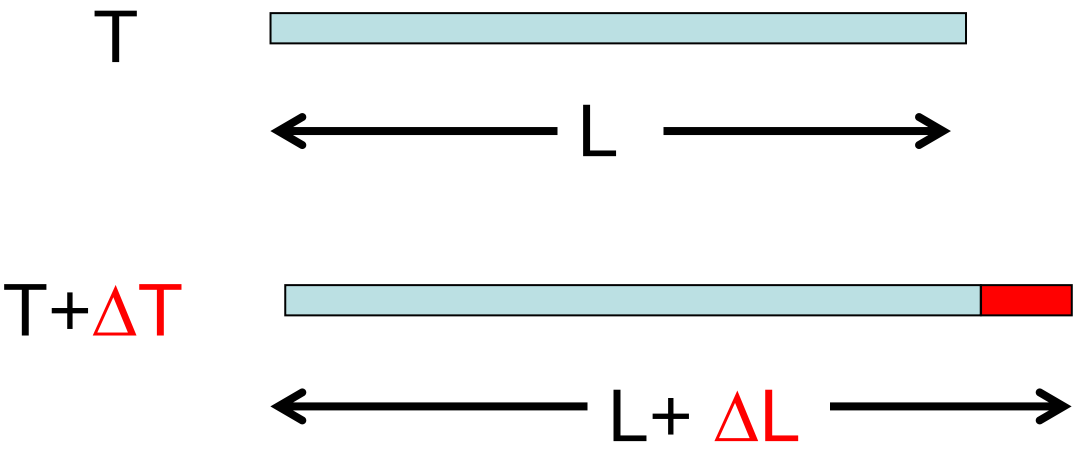
$5^0C = 39^0F$

$5C^0 = 5K$

$5C^0 = 9F^0$

19-5 Thermal expansion

Linear Expansion



T

L

$T+\Delta T$

$L+\Delta L$

$$\boxed{\Delta L = L\,\alpha\,\Delta T}$$

Coefficient of linear expansion

19-5 Thermal expansion

Example

For Aluminum $\alpha = 23\ 10^{-6}/C^0$

$$\Delta L = L\ \alpha\ \Delta T$$

An Aluminum rod of a length of 1 m will elongate by 23 μm if its temperature raised by 1 degree Celsius

19-5 Thermal expansion

Volume Expansion

Change in volume

Original volume

$$\boxed{\Delta V = V \beta \Delta T}$$

Coefficient of volume expansion

Change in temperature

$$\boxed{\beta = 3\alpha}$$

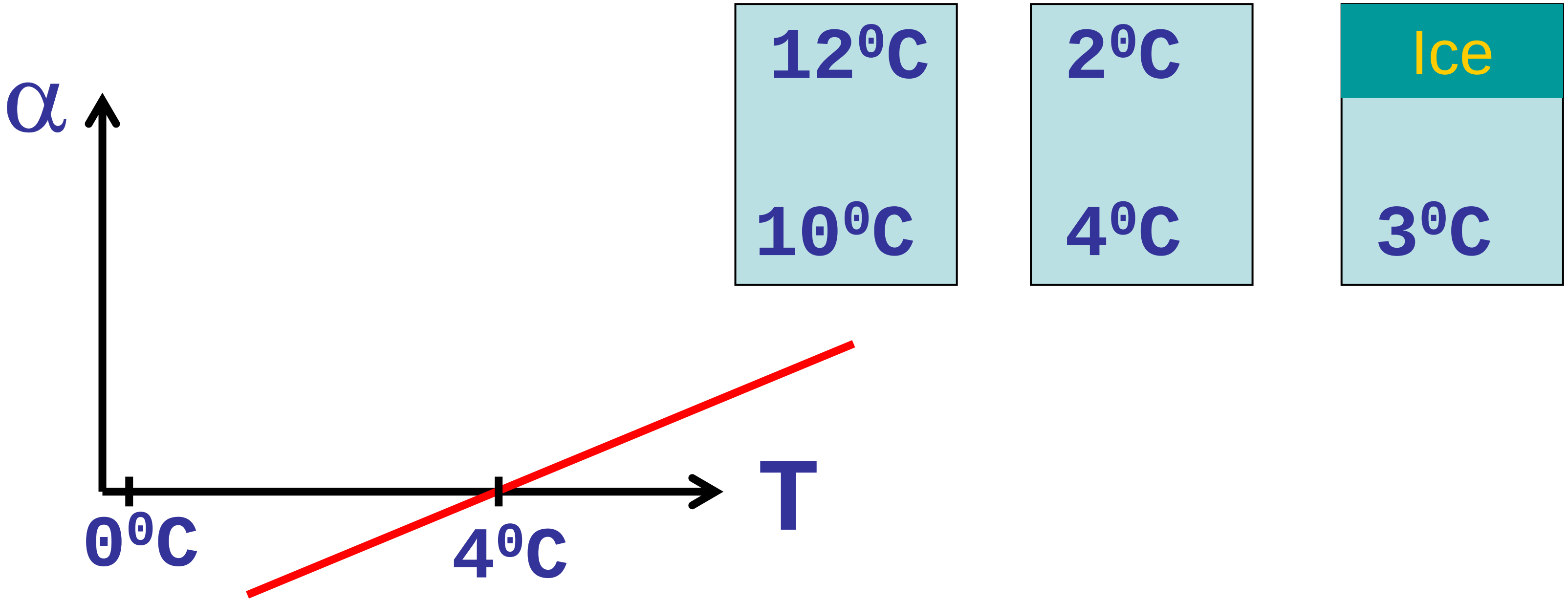
19-5 Thermal expansion

$$\alpha$$

Coefficient of linear expansion varies with temperature,
for most practical purposes you may assume it constant

19-5 Thermal expansion

Special case: water



Ice formed on surface

Below 4^0C, higher temperature means smaller volume or higer density

Above 4^0C, higher temperature means bigger volume or lower density

19-5 Thermal expansion

Check point 2

19-5 Thermal expansion

Sample Problem 19-2

A truck loaded with 37,000 L of diesel moves from a hot to a cold area. The change in temperature is 23K. How many liters are remaining in the truck?
The coefficient of volume expansion for diesel is $9.5\times10^{-4}/C^0$.

$\Delta T = T_f - T_i$

$\Delta V = V \beta \Delta T$

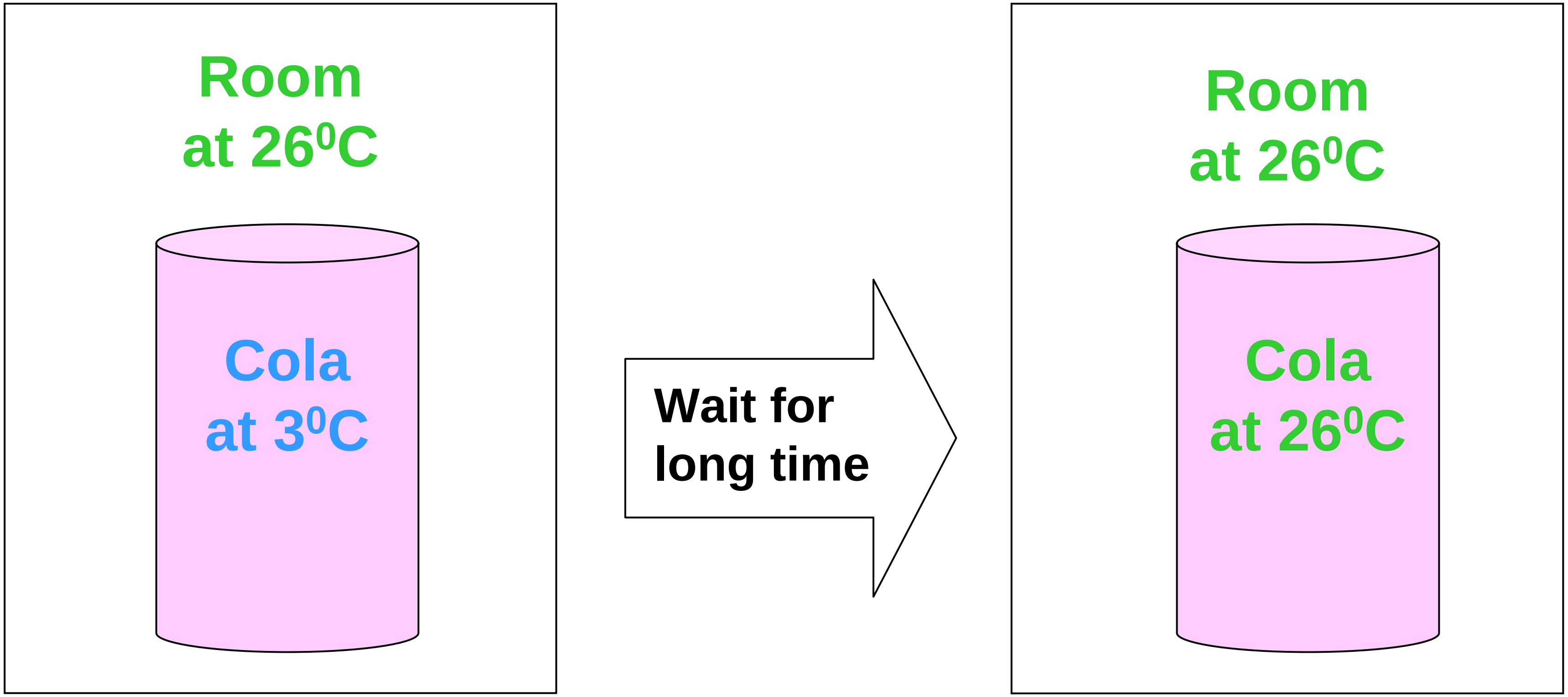
$\Delta V = (37{,}000)\,(9.5\times10^{-4})\,(-23)$

$= -808 \text{ L}$

$\Delta V = V_f - V_i \rightarrow V_f = V_i + \Delta V$

Liters remaining in the truck = 37,000+(- 808) = 36,190 L

19-6 Temperature and Heat



Room
at 26^0C

Cola
at 3^0C

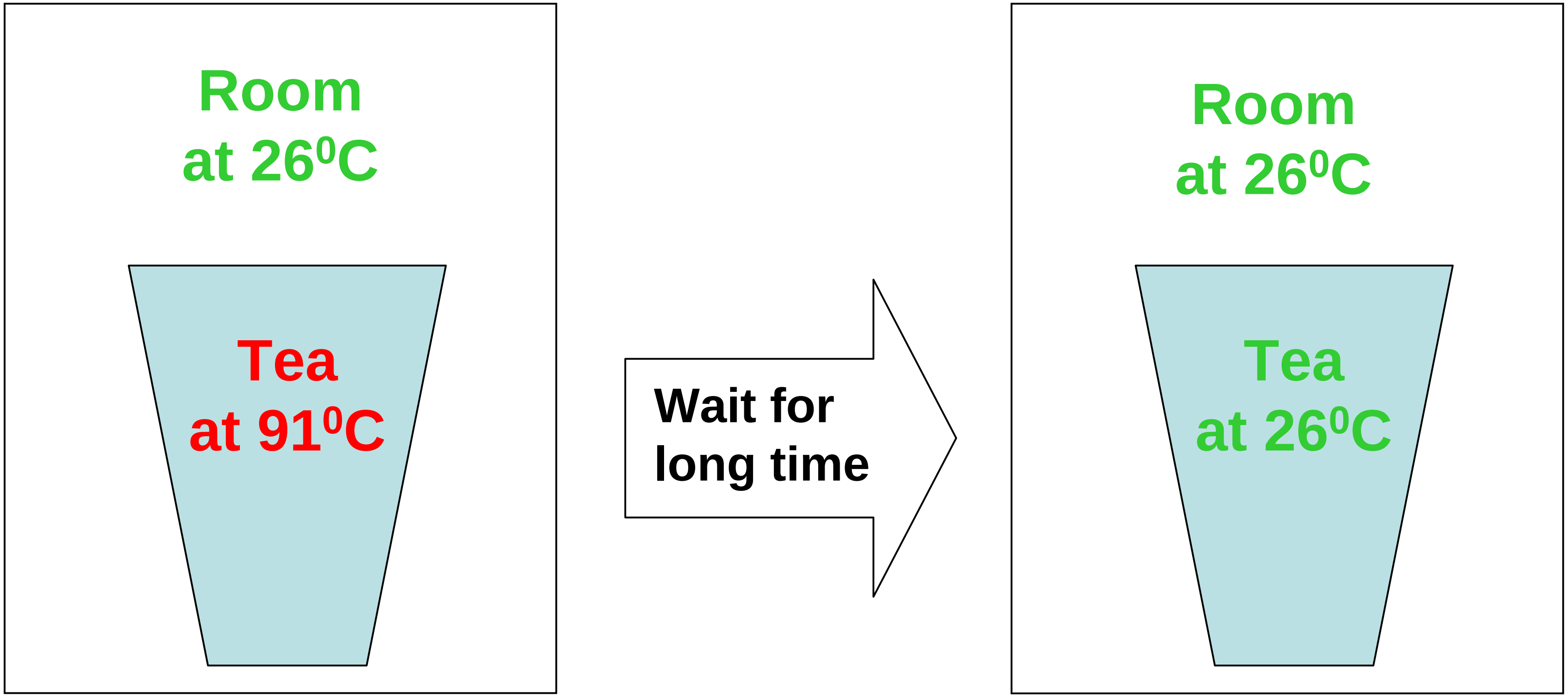
Wait for
long time

Room
at 26^0C

Cola
at 26^0C

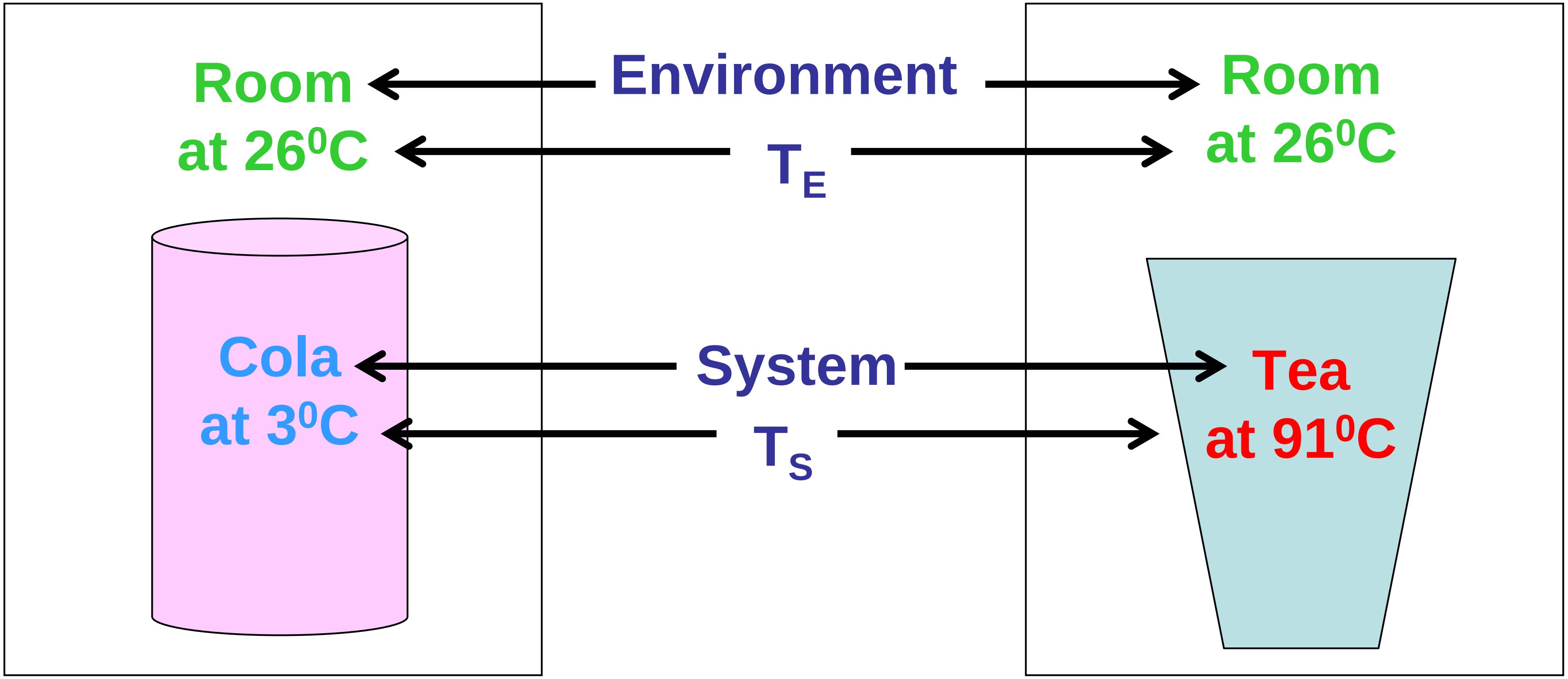
Change in temperature is due to the transfer of energy between the thermal energy of the can of cola and the thermal energy of the room

19-6 Temperature and Heat



Change in temperature is due to the transfer of energy between the thermal energy of the cup of tea and the thermal energy of the room

19-6 Temperature and Heat



Room

at 26^0C

Environment

T_E

Room

at 26^0C

Cola

at 3^0C

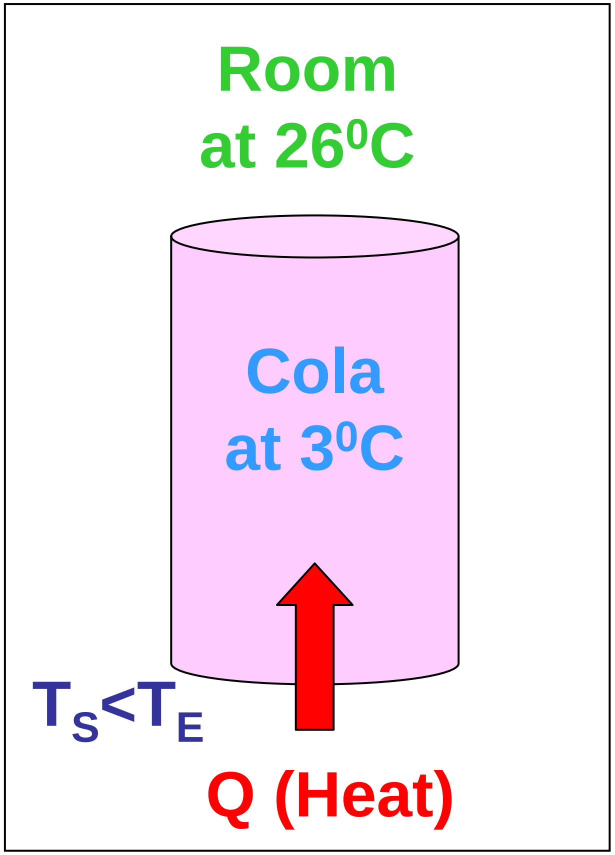
System

T_S

Tea

at 91^0C

19-6 Temperature and Heat



Room

at 26^0C

Cola

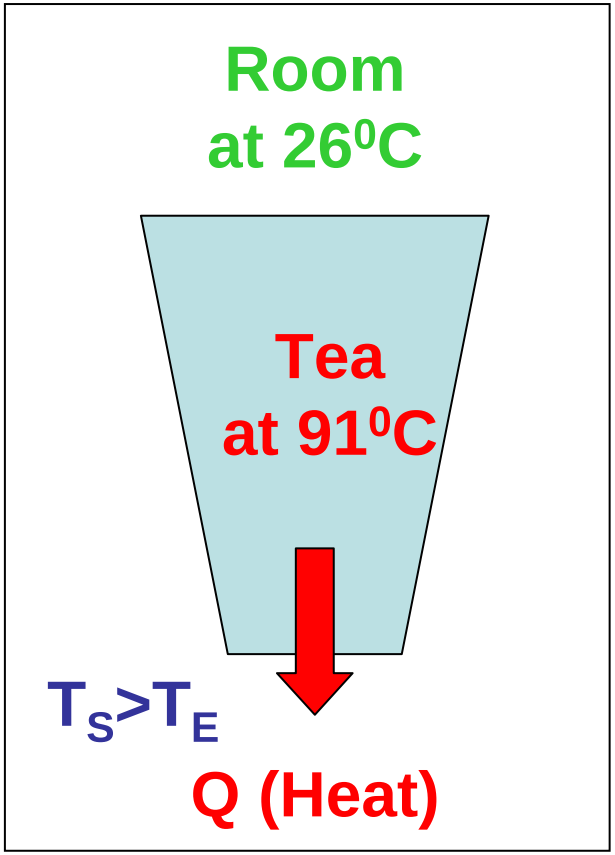
at 3^0C

$T_S<T_E$

Q (Heat)

Heat Absorbed

$Q > 0$



Room

at 26^0C

Tea

at 91^0C

$T_S>T_E$

Q (Heat)

Heat Released

$Q < 0$

19-6 Temperature and Heat

Heat is the energy that is transferred between a system and its environment because of a temperature difference that exists between them

SI unit for Heat is joule (J)

Heat is also measured in calorie (cal)

Heat is also measured in British Thermal unit (BTU)

$$1\ \text{cal} = 3.969 \times 10^{-3}\ \text{Btu} = 4.1860\ \text{J}$$

19-7 The Absorption of Heat by Solids and Liquids

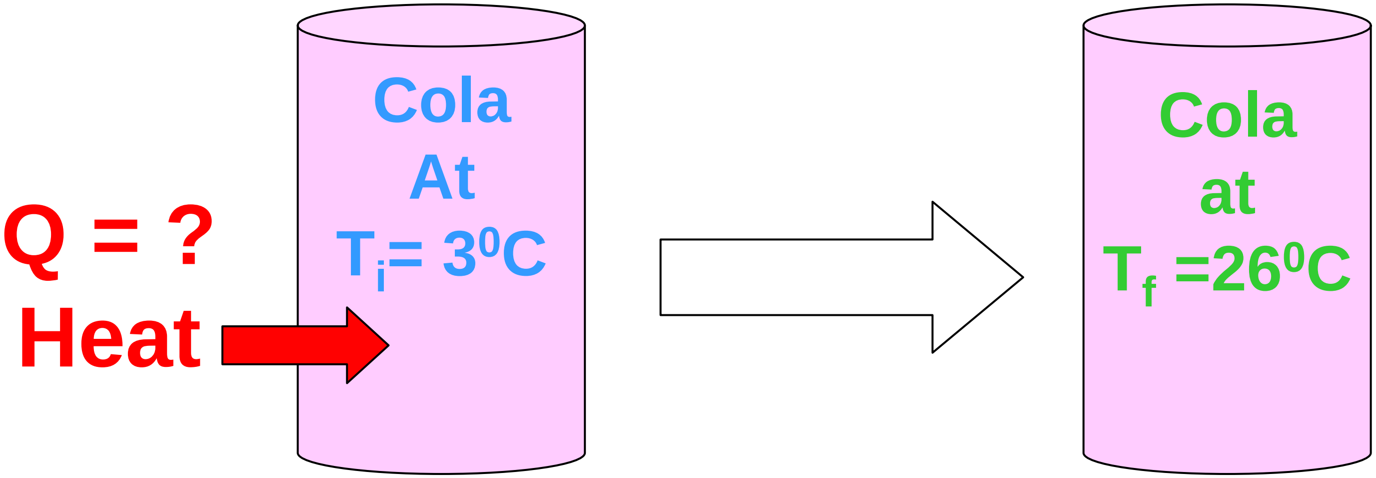
Heat Capacity

$$Q = C(T_f - T_i) = C\Delta T$$

Heat (J)

Heat Capacity (J/K)

Change in temperature (K)



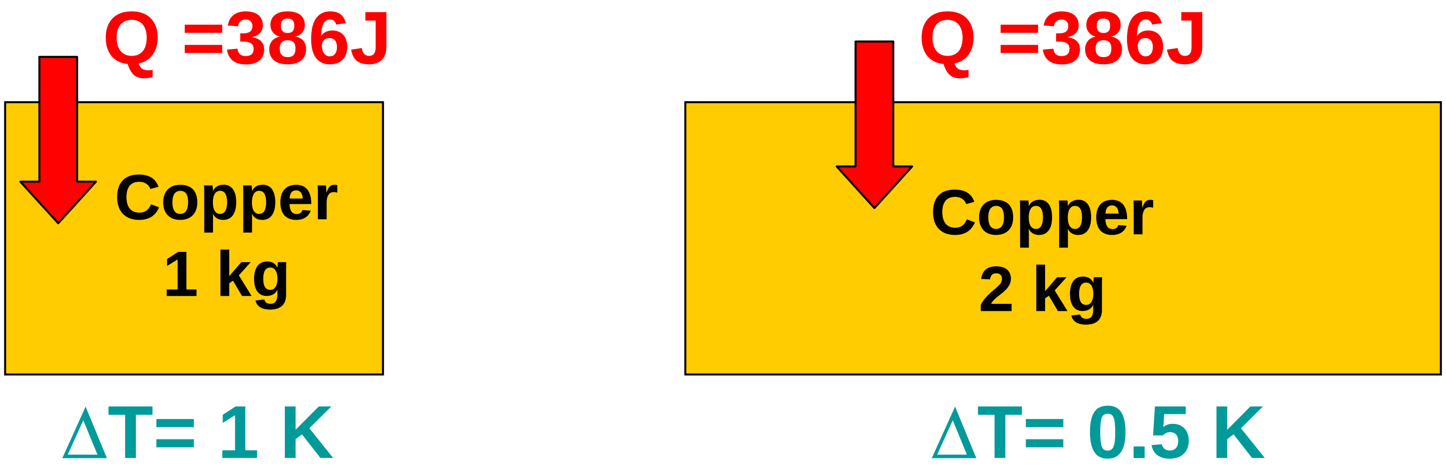
Q = ?

Heat

Cola At $T_i = 3^0C$

Cola at $T_f = 26^0C$

19-7 The Absorption of Heat by Solids and Liquids



Q =386J

Copper
1 kg

ΔT= 1 K

Q =386J

Copper
2 kg

ΔT= 0.5 K

define a quantity that is independent of the mass of the material

$$\frac{\text{Heat Capacity}}{\text{Mass}} = \text{Specific Heat}$$

$$\frac{C}{m} = c$$

19-7 The Absorption of Heat by Solids and Liquids

Specific Heat

$$Q = C(T_f - T_i) = C\Delta T$$

$$\boxed{Q = c\ m\ \Delta T}$$

Heat
(J)

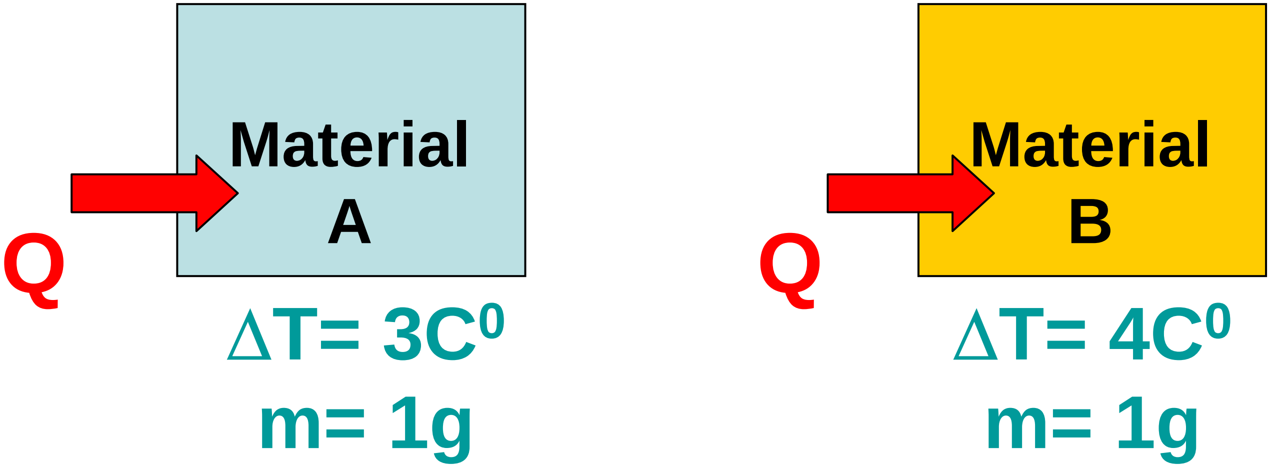
Specific Heat
(J/kg.K)

mass
(kg)

Change in
temperature (K)
$T_f - T_i$

19-7 The Absorption of Heat by Solids and Liquids

Check point 3



Q

Material A

$\Delta T = 3C^0$

$m = 1g$

Q

Material B

$\Delta T = 4C^0$

$m = 1g$

Which material has greater specific heat ?

Answer : material A

$$Q = c\ m\ \Delta T$$

19-7 The Absorption of Heat by Solids and Liquids

Molar specific heat

Heat capacity = (Specific heat) (Mass)

Sometimes the amount of material is specified in number of moles instead of mass

Heat capacity = (Molar specific heat) (Number of moles)

1 Mole = 6.02×10^{23} elementary units

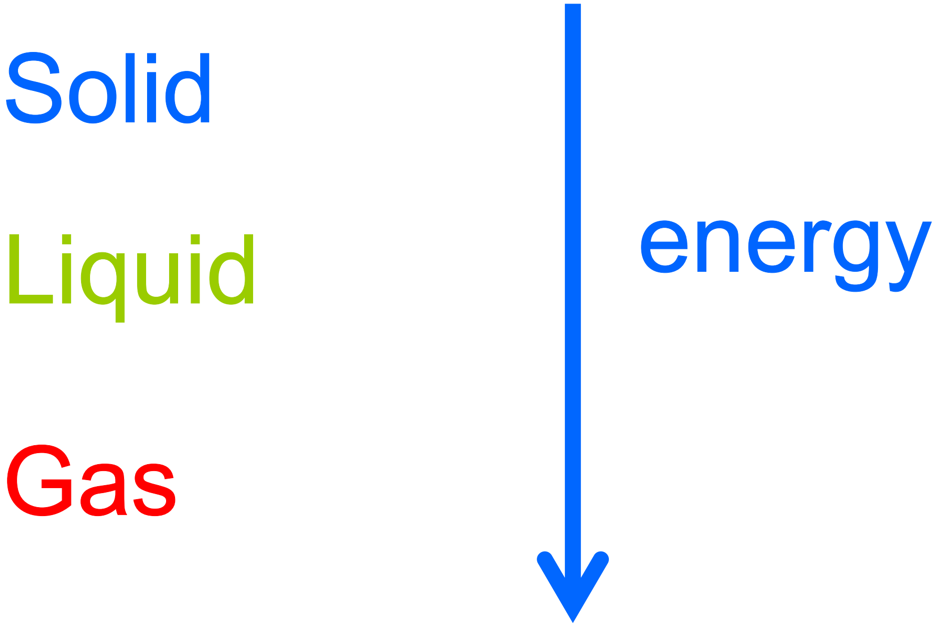
1 Mole of copper = 6.02×10^{23} copper atoms

1 Mole of students = 6.02×10^{23} students

19-7 The Absorption of Heat by Solids and Liquids

Heat of transformation

Matter can exist in three states (phases)



19-7 The Absorption of Heat by Solids and Liquids

Heat of transformation

Solid (Ice) → Melting (Fusing), Energy absorbed → **Liquid** (water)

Same Temperature

Liquid (water) → Freezing, Energy Released → **Solid** (Ice)

Same Temperature

19-7 The Absorption of Heat by Solids and Liquids

Heat of transformation

Liquid $\xrightarrow[\text{Energy absorbed}]{\text{Vaporizing}}$ Gas

water → steam

Same Temperature

Gas $\xrightarrow[\text{Energy Released}]{\text{Condensing}}$ Liquid

steam → water

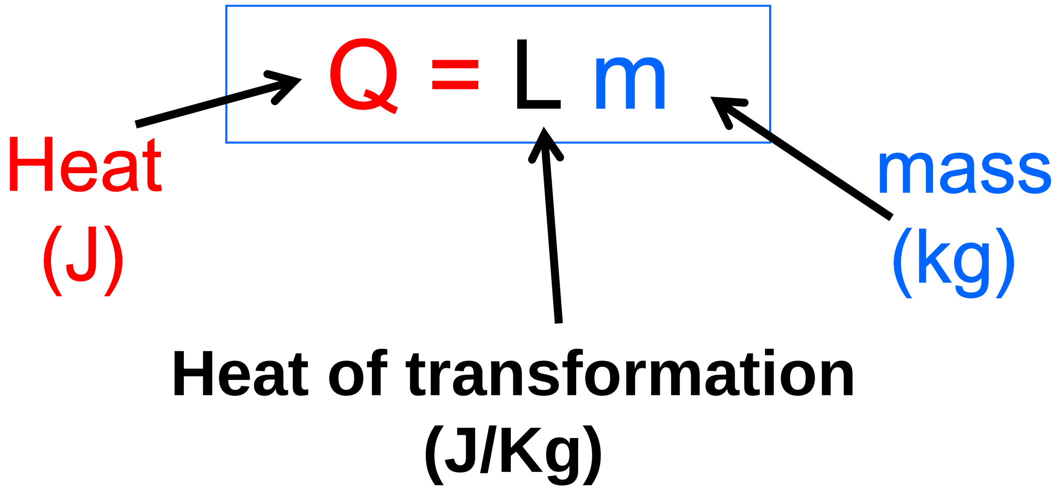
Same Temperature

19-7 The Absorption of Heat by Solids and Liquids

State 1 → State 2

Same Temperature

Heat of transformation = Heat per unit mass required to change a substance form one state to another



$$\boxed{Q = L\,m}$$

Heat (J)

Heat of transformation (J/Kg)

mass (kg)

19-7 The Absorption of Heat by Solids and Liquids

State 1 → State 2

L = Heat of Transformation

Liquid → Gas

L_V = Heat of vaporization

Solid → Liquid

L_F = Heat of fusion

19-7 The Absorption of Heat by Solids and Liquids

Example

Ice → Ice C_{Ice} = 2.22 kJ/kg K

Ice → Water L_F = 333 kJ/kg

Water → Water C_{Water} = 4.19 kJ/Kg K

Water → Steam L_V = 2256 KJ/kg

19-7 The Absorption of Heat by Solids and Liquids

Sample Problem 19-3

m = 720 g

$$\boxed{\begin{array}{c}\text{Ice}\\ T = -10^0\text{C}\end{array}} \xrightarrow{\text{Heat?}} \boxed{\begin{array}{c}\text{Water}\\ T = 15^0\text{C}\end{array}}$$

$$\boxed{\begin{array}{c}\text{Ice}\\ T = -10^0\text{C}\end{array}} \rightarrow \boxed{\begin{array}{c}\text{Ice}\\ T = 0^0\text{C}\end{array}} \rightarrow \boxed{\begin{array}{c}\text{Water}\\ T = 0^0\text{C}\end{array}} \rightarrow \boxed{\begin{array}{c}\text{Water}\\ T = 15^0\text{C}\end{array}}$$

$Q_1=c_{ice}m(T_f-T_i)$

$Q_2=L_Fm$

$Q_2=c_{water}m(T_f-T_i)$

$Q_1=(2220)(.72)(0-(-10))$

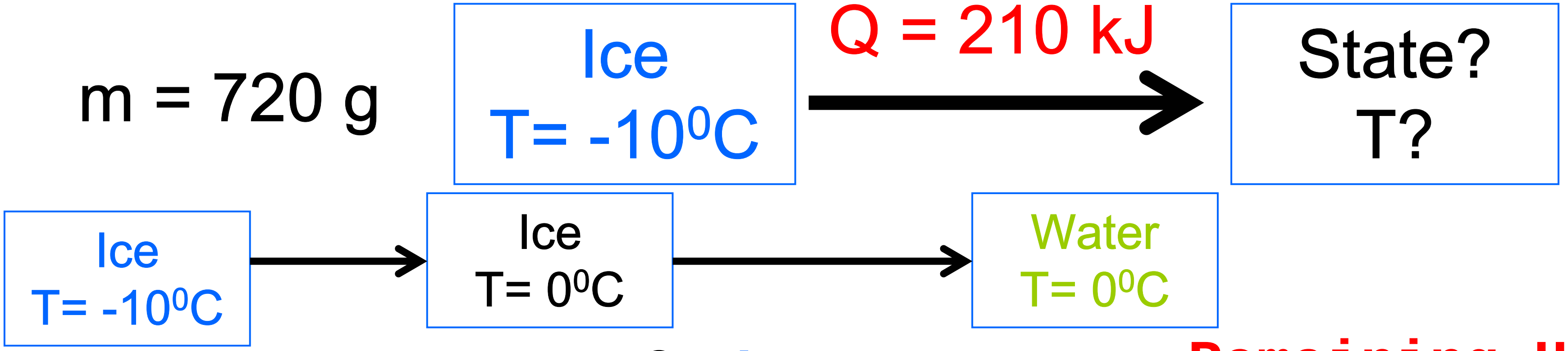
$Q_2= (333X10^3) (.72)$

$Q_3= (4190) (.72) (15-0)$

$$Q = Q_1+Q_2+Q_3 = 300 \text{ kJ}$$

19-7 The Absorption of Heat by Solids and Liquids

Sample Problem 19-3 continue



m = 720 g

Ice
$T = -10^0C$

$\xrightarrow{Q = 210\text{ kJ}}$

State?
T?

Ice
$T = -10^0C$

$\rightarrow$

Ice
$T = 0^0C$

$\rightarrow$

Water
$T = 0^0C$

$Q_1 = c_{ice} m (T_f - T_i)$

$Q_1 = 15.98$ kJ

$Q_1 < Q$

$Q_2 = L_F m$

$Q_2 = 239.8$ kJ

$Q_1 + Q_2 = 245.78$ kJ

$Q_1 + Q_2 > Q$

Remaining Heat to melt ice

$Q_{rem} = Q - Q_1$

$= 210\text{ k} - 15.98\text{ k}$

$= 194$ kJ

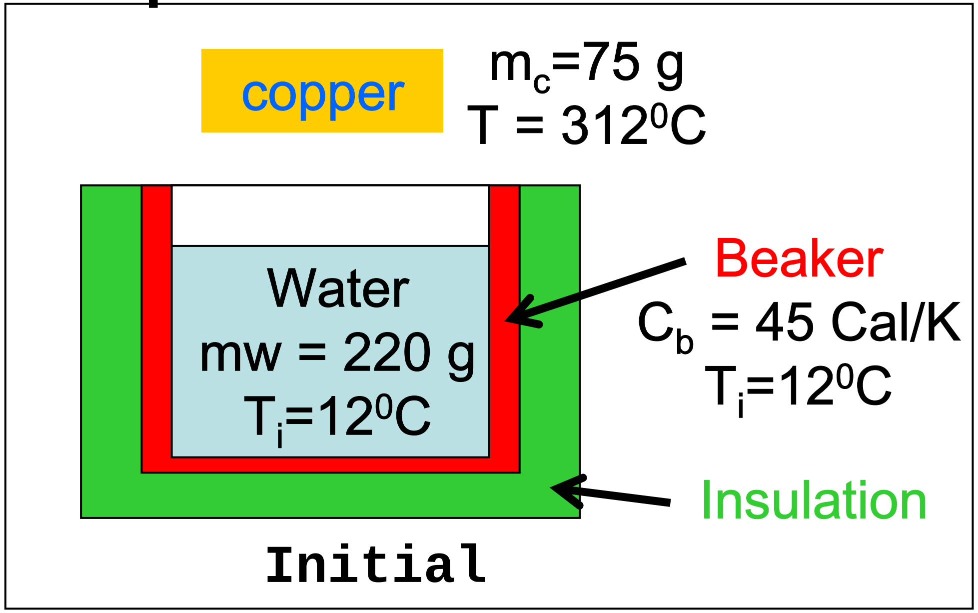
Quantity of ice melted $= \dfrac{Q_{rem}}{L_F} = \dfrac{194\text{ k}}{333\text{ k}} = 580$ g

Quantity of ice remaining = 720 – 580 = 140 g

We have 580 g water and 140 g ice at 0^0C

19-7 The Absorption of Heat by Solids and Liquids

Sample Problem 19-4



copper

$m_c = 75$ g

$T = 312^0$C

Water

mw = 220 g

$T_i = 12^0$C

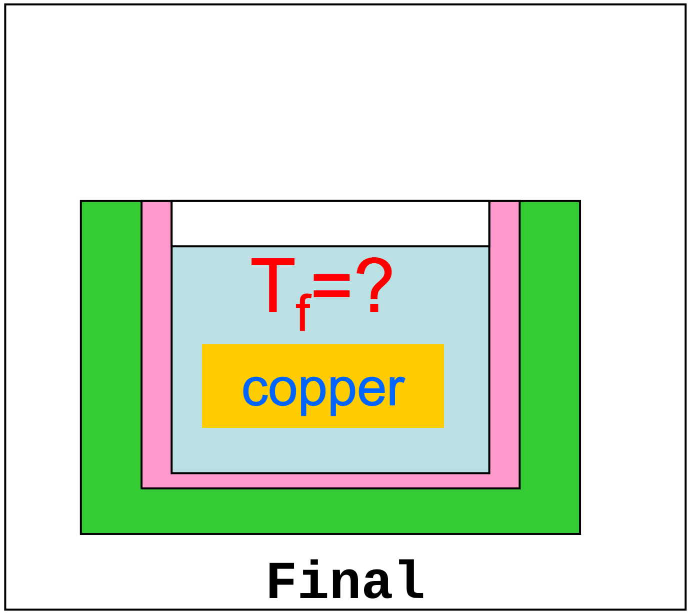
Beaker

$C_b = 45$ Cal/K

$T_i = 12^0$C

Insulation

Initial



$T_f = ?$

copper

Final

Since the system is isolated,
the total energy of the system does not change

Heat transfer to copper + Heat transfer to water + Heat transfer to beaker = 0

$$Q_c + Q_w + Q_b = 0$$

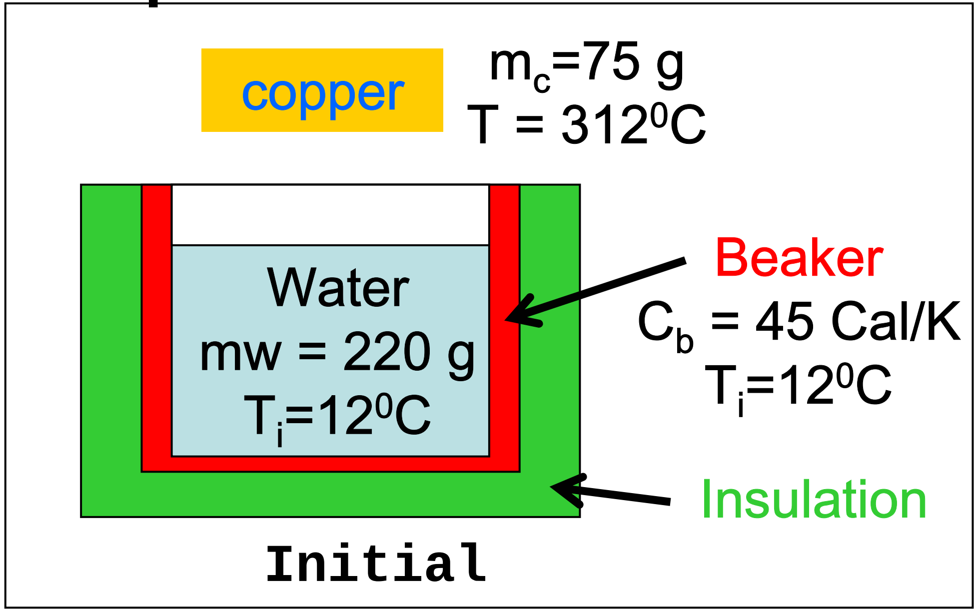
$$c_c m_c (T_f - T) + c_w m_w (T_f - T_i) + C_b (T_f - T_i) = 0$$

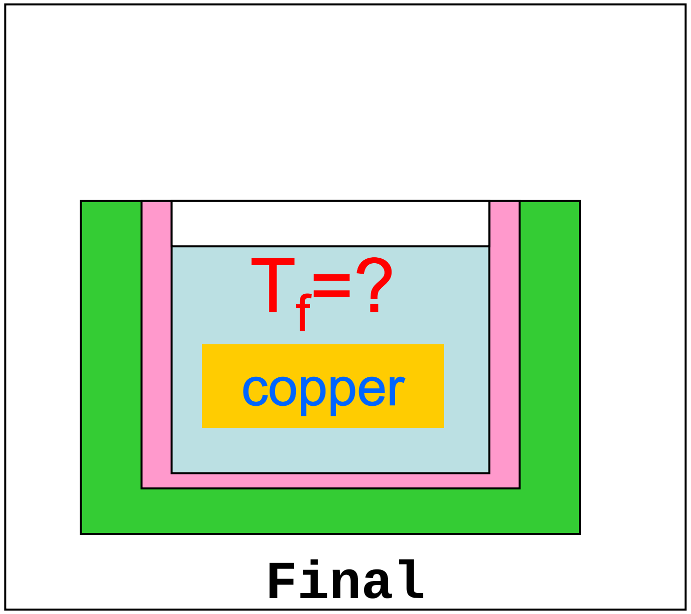
Solve for T_f

$$T_f (c_c m_c + c_w m_w + C_b) - c_c m_c T - c_w m_w T_i - C_b T_i = 0$$

19-7 The Absorption of Heat by Solids and Liquids

Sample Problem 19-4 Continue





$$T_f = \frac{c_c\, m_c\, T + c_w\, m_w\, T_i + C_b\, T_i}{c_c\, m_c + c_w\, m_w + C_b}$$

$$= \frac{(.0923\,\text{cal/g.K})(75\,\text{g})\left(312^0\,\text{C}\right) + (1\,\text{cal/g.K})(220\,\text{g})\left(12^0\,\text{C}\right) + (45\,\text{cal/K})\left(12^0\,\text{C}\right)}{(.0923\,\text{cal/g.K})(75\,\text{g}) + (1\,\text{cal/g.K})(12\,\text{g}) + (45\,\text{cal/K})}$$

$$= 19.6^0\text{C}$$

19-8 A Closer Look at Heat and Work

How energy can be transferred as heat and work between a system and its environment?

Work done by the gas for a small change in volume

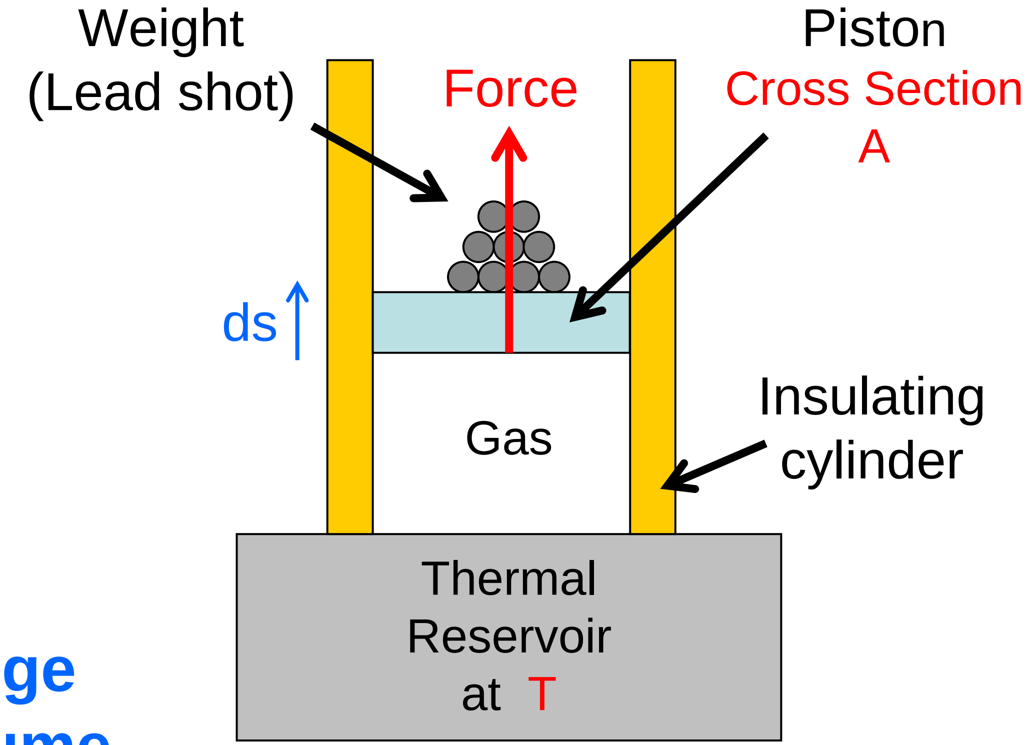
$$dW = F\,ds$$

$$dW = PA\,ds$$

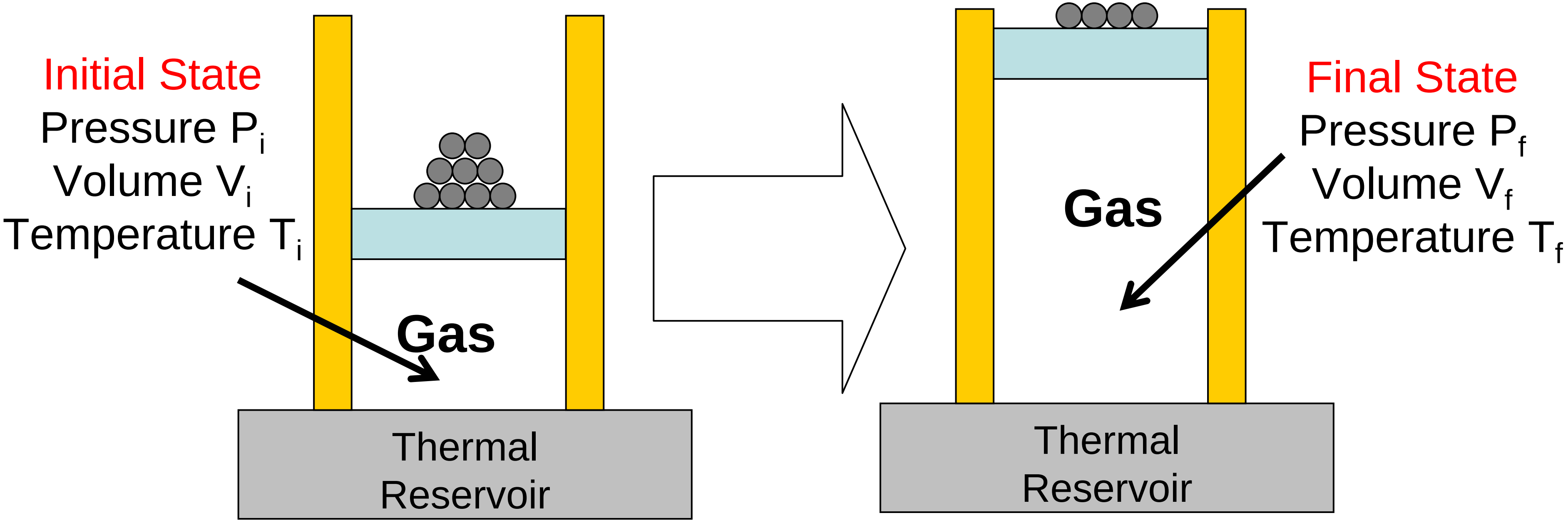
$$dW = P\,dV$$

Pressure

Change in Volume



19-8 A Closer Look at Heat and Work



Initial State

Pressure P_i

Volume V_i

Temperature T_i

Final State

Pressure P_f

Volume V_f

Temperature T_f

Thermodynamics process

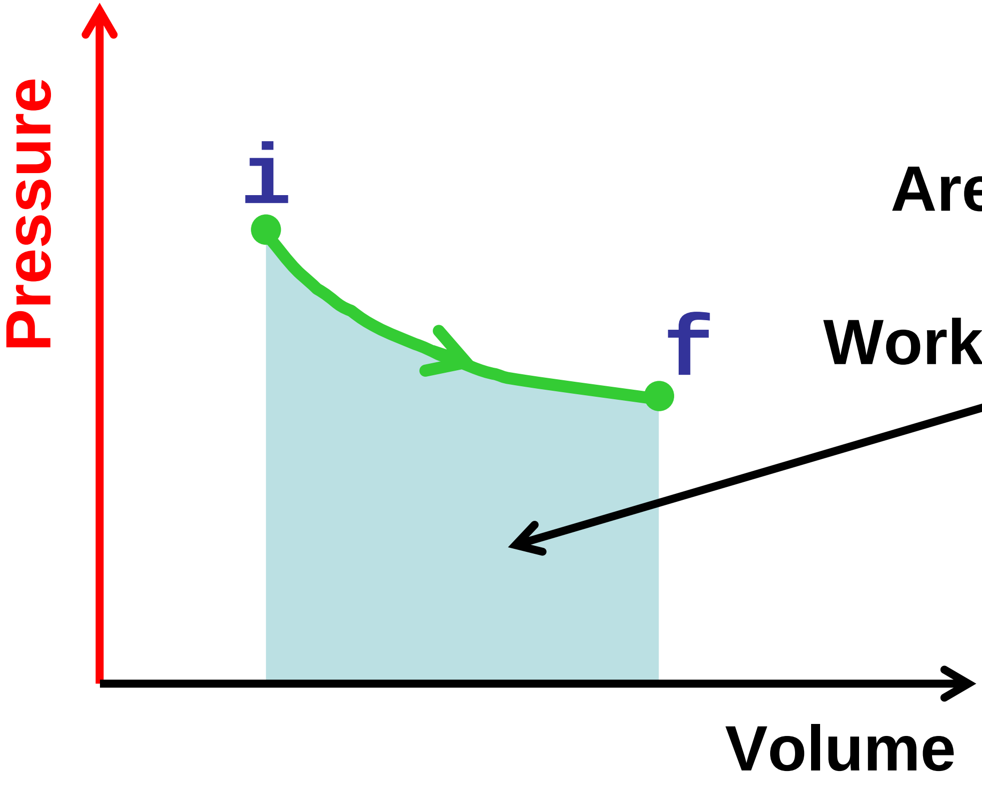
Work done by the system (gas)

$$\boxed{W = \int_{V_i}^{V_f} P\,dV}$$

19-8 A Closer Look at Heat and Work

$$\boxed{W = \int_{V_i}^{V_f} P\,dV}$$

To find the work, we need to know P as a function of V



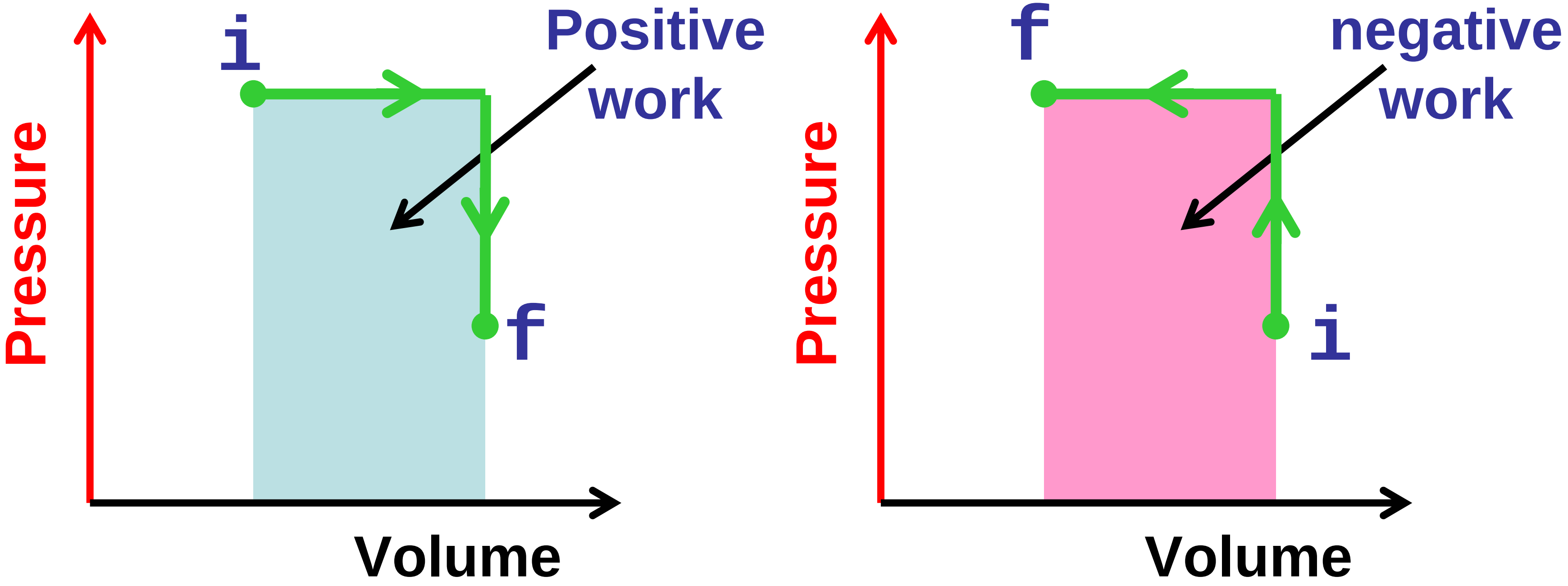
Area under the curve

=

Work done by the system

19-8 A Closer Look at Heat and Work

$$\boxed{W = \int_{V_i}^{V_f} P\,dV}$$



Work is negative,

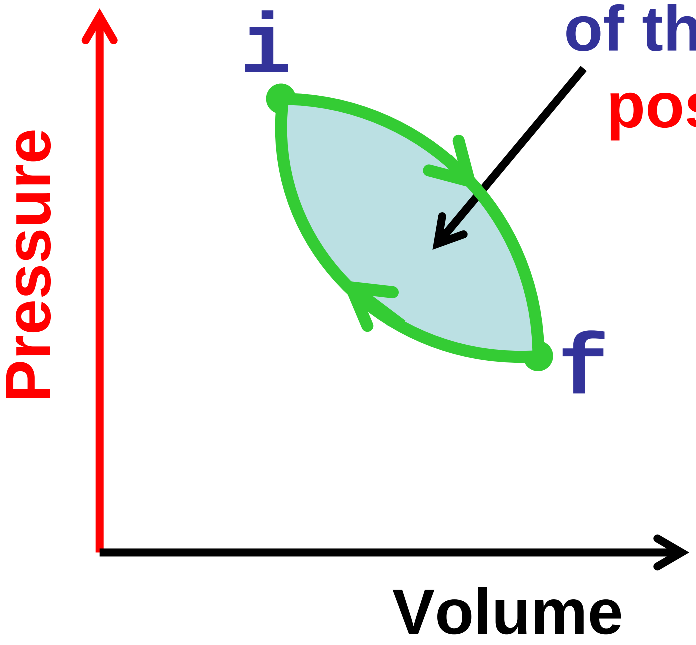
when the final volume is smaller than the initial volume

compression

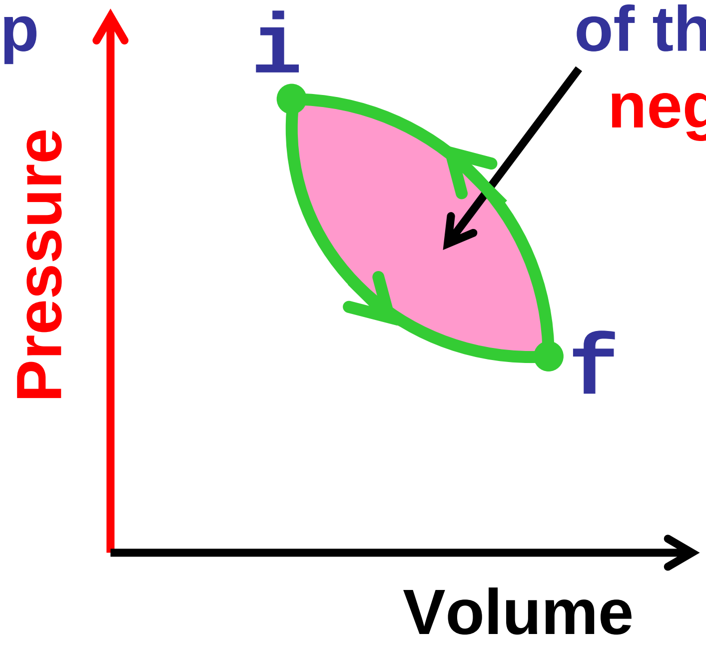
19-8 A Closer Look at Heat and Work

$$\boxed{W = \int_{V_i}^{V_f} P\,dV}$$

Thermodynamics cycles



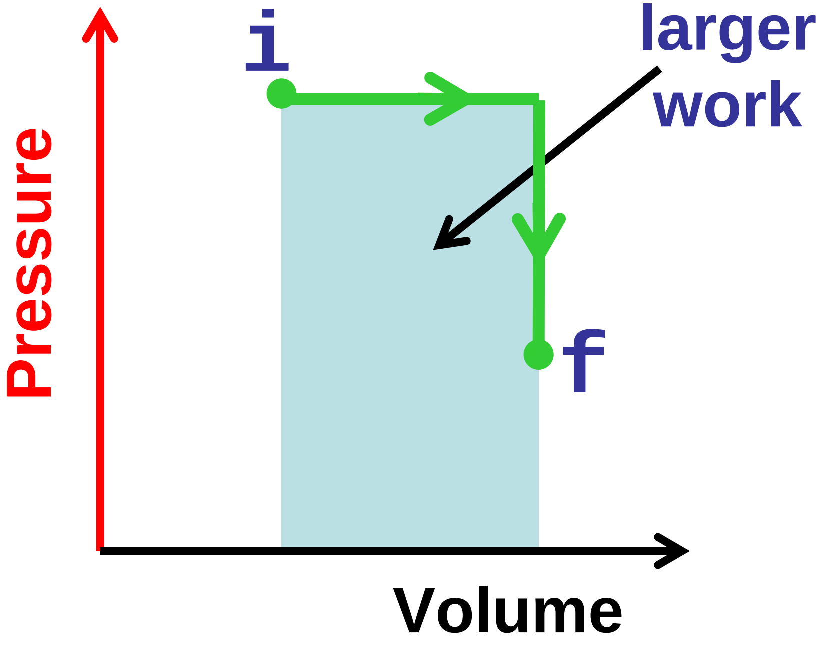
Work = area of the loop positive

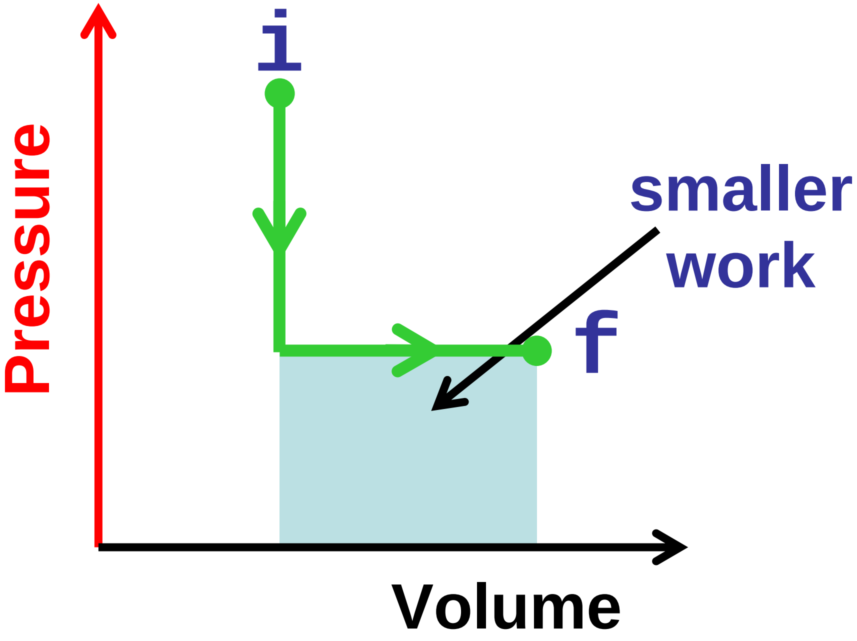


Work = area of the loop negative

19-8 A Closer Look at Heat and Work

$$\boxed{W = \int_{V_i}^{V_f} P\,dV}$$



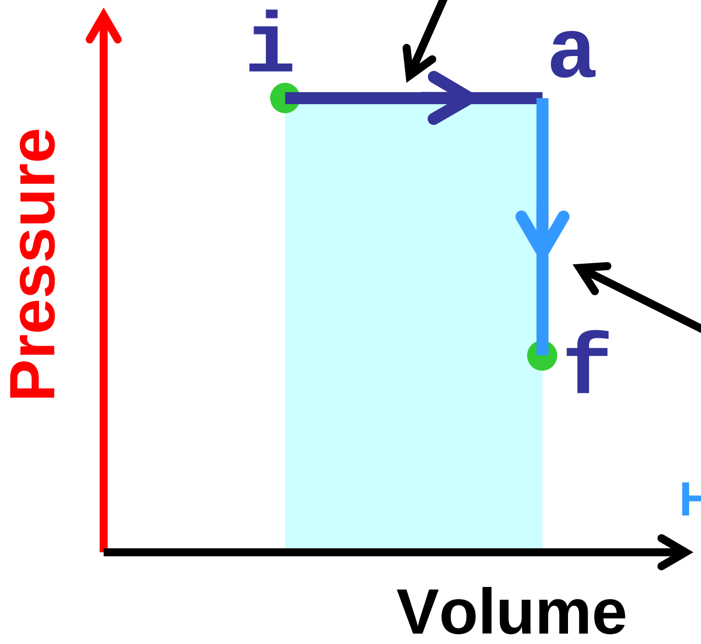


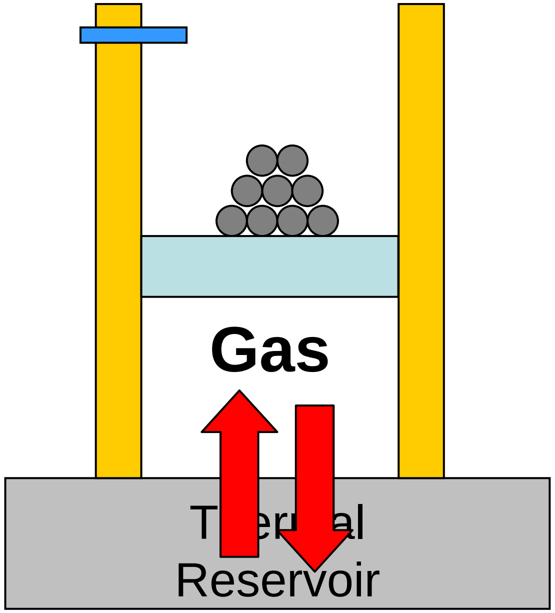
Work depends on the path

19-8 A Closer Look at Heat and Work

Example

i to a
Fix pressure
Increase T
Heat flows to the system
W=area under the curve





a to f
Fix volume
Decrease T
Heat flows out of the system
W=0

Work done on the system is path dependent
Heat flow to the system is path dependent

19-8 A closer Look at Heat and Word

Check point 4

19-9 First Law of Thermodynamics

W is path dependent
Q is path dependent

From experiments, Q-W is independent of the path

Q-W is related to some property of the system

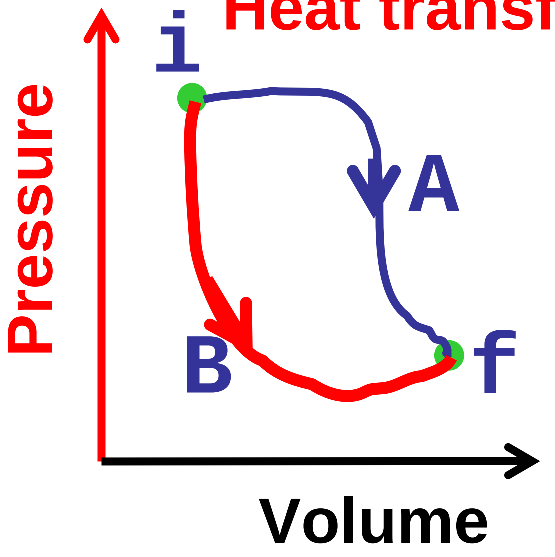
Internal Energy

$$\Delta E_{int} = Q - W$$

`First Law of thermodynamics`

Change in the internal energy of a system =

Heat transferred to the system – Work done by it



19-9 First Law of Thermodynamics

First Law of Thermodynamics

$$\Delta E_{int} = Q - W$$

The internal energy of a system
tends to increase if energy is added as heat Q to the system
and
tends to decrease if energy is lost as work W done by the system

Conservation of energy

19-9 First Law of Thermodynamics

Check point 5

19-10 Some Special Cases of the First Law of Thermodynamics

Special Cases of the First Law of Thermodynamics

$$\boxed{\Delta E_{int} = Q - W}$$

Adiabatic processes

Constant-volume processes

Closed cycle processes

Free expansion processes

19-10 Some Special Cases of the First Law of Thermodynamics

Adiabatic processes

No heat transfer to the system

$Q=0$

Either

System is well insulated

Or

Process occurs so rapidly

$$\boxed{\Delta E_{int} = Q - W} \longrightarrow \boxed{\Delta E_{int} = - W}$$

19-10 Some Special Cases of the First Law of Thermodynamics

Constant-volume processes

$$W = \int_V^V P dV = 0$$

$$\boxed{\Delta E_{int} = Q - W} \Longrightarrow \boxed{\Delta E_{int} = Q}$$

Cyclical processes

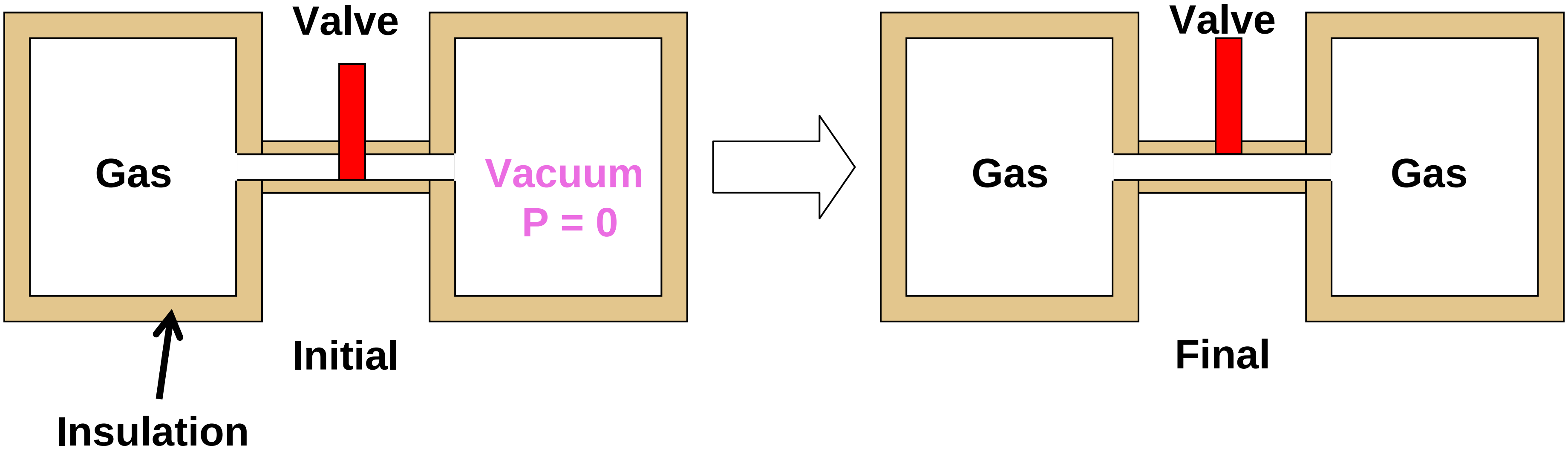
Final state = initial state

$\Delta E_{int} = 0$

$$\boxed{\Delta E_{int} = Q - W} \Longrightarrow \boxed{Q = W}$$

19-10 Some Special Cases of the First Law of Thermodynamics

Free expansions



System is insulated → $Q = 0$

$$W = \int_{V_i}^{V_f} P\,dV = \int_{V_i}^{V_f} 0\,dV = 0$$

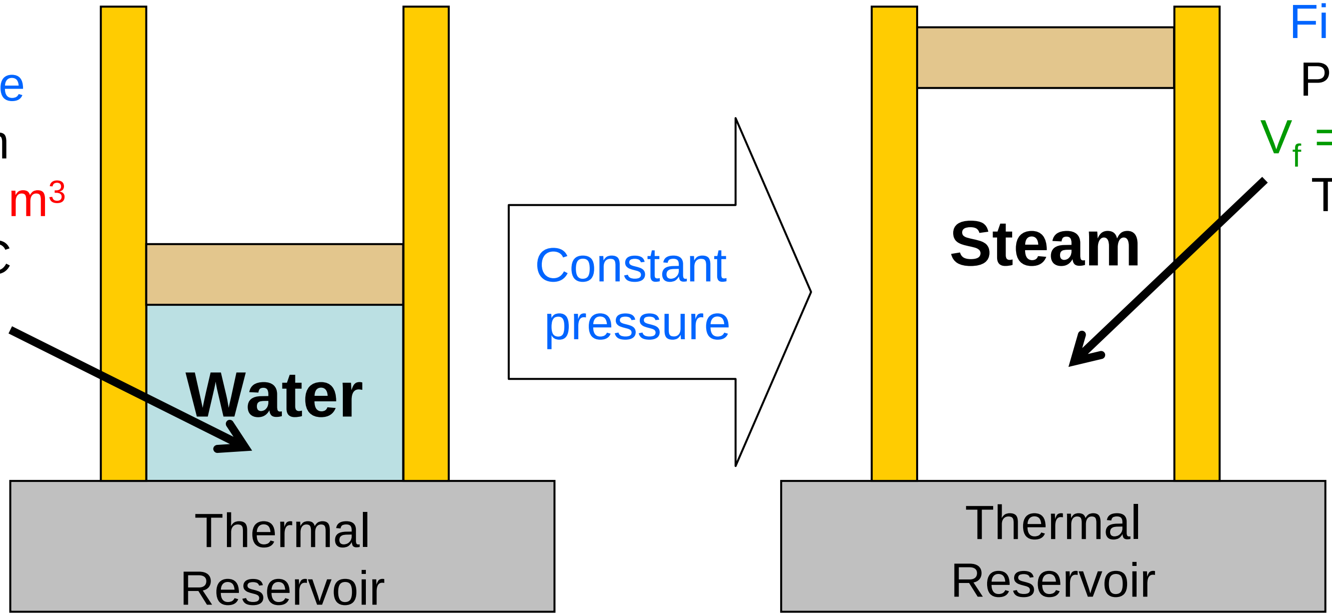
$$\boxed{\Delta E_{int} = Q - W} \longrightarrow \boxed{\Delta E_{int} = 0}$$

19-10 Some Special Cases of the First Law of Thermodynamics

Check point 6

19-10 Some Special Cases of the First Law of Thermodynamics

Sample Problem 19-5



Initial State
P_i= 1 Atm
$V_i = 1 \times 10^{-3}\ m^3$
T_i=100^{0}C
m=1kg

Final State
P_f= 1 Atm
$V_f = 1.671\ m^3$
T_f=100^{0}C
m=1kg

Work done by the system?

$$W = \int_{V_i}^{V_f} P dV = P \int_{V_i}^{V_f} dV = P(V_f - V_i)$$

$$W = (1.01\times10^5 Pa)(1.671m^3 - 1\times10^{-3}m^3) = 169kJ$$

Energy transferred as heat to the system?

$$Q = L_v m = (2256kJ/kg)\ (1kg) = 2256\ kJ$$

Change in the system’s internal energy?

$$\Delta E_{int} = Q - W = 2256\ kJ - 169kJ$$

19-11 Heat Transfer Mechanism

How does heat transfer take place?

Conduction

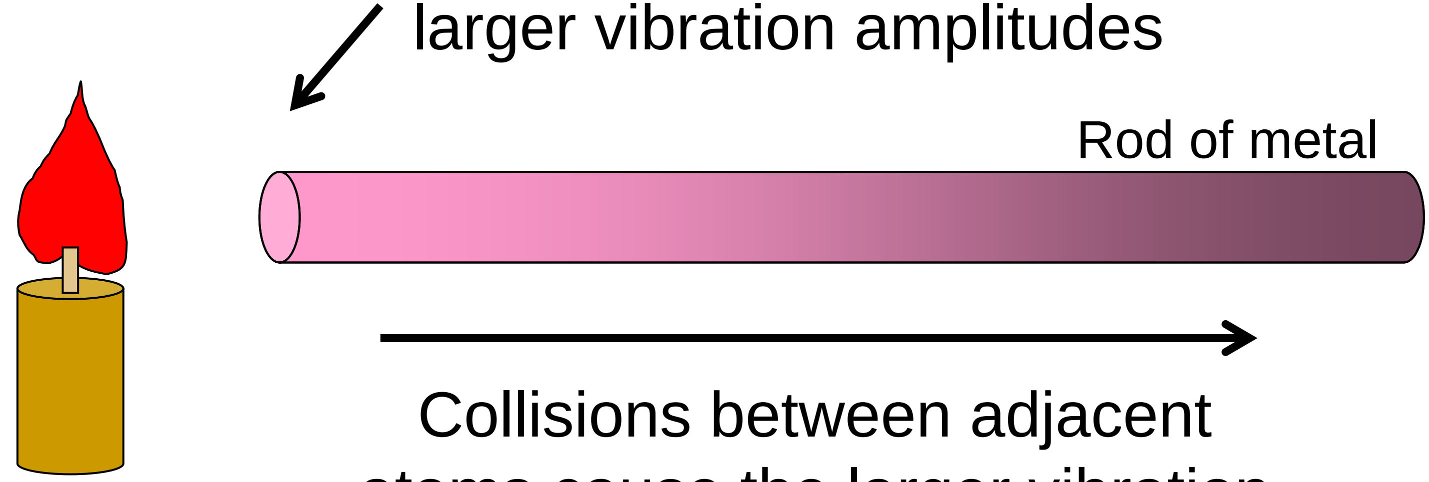
Convection

Radiation

19-11 Heat Transfer Mechanism

Conduction

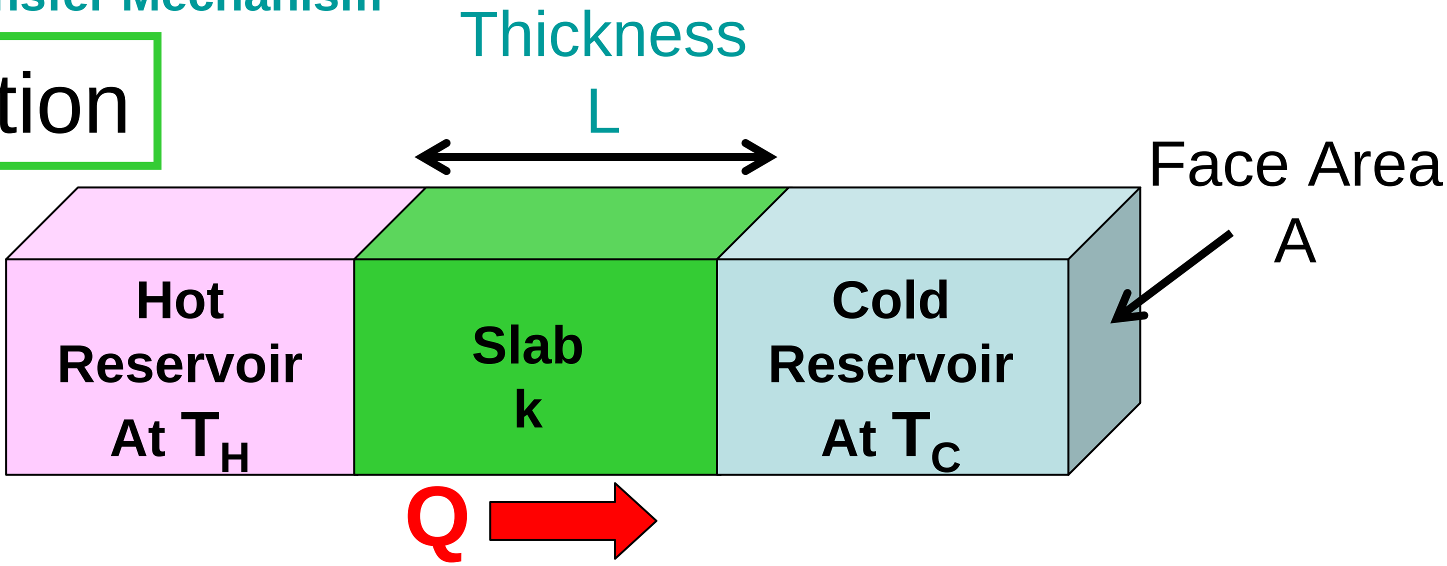
At high temperatures, atoms and electrons have larger vibration amplitudes



Collisions between adjacent atoms cause the larger vibration amplitudes to move from one region to another, and thus heat is transferred along the material

19-11 Heat Transfer Mechanism

Conduction



Conduction rate
(the amount of energy transferred per unit time)

Heat

Hot Reservoir temperature

Cold Reservoir temperature

$$P_{con} = \frac{Q}{t} = kA\frac{T_H - T_C}{L}$$

Time

Thermal conductivity

19-11 Heat Transfer Mechanism

Conduction

Substance	k (W/m·K)
copper	401.
Air	0.026
Glass	1.0

$$P_{con} = kA\frac{T_H - T_C}{L}$$

Thermal conductivity

Constant

depends on the material

Thermal Resistance
(R-Value)

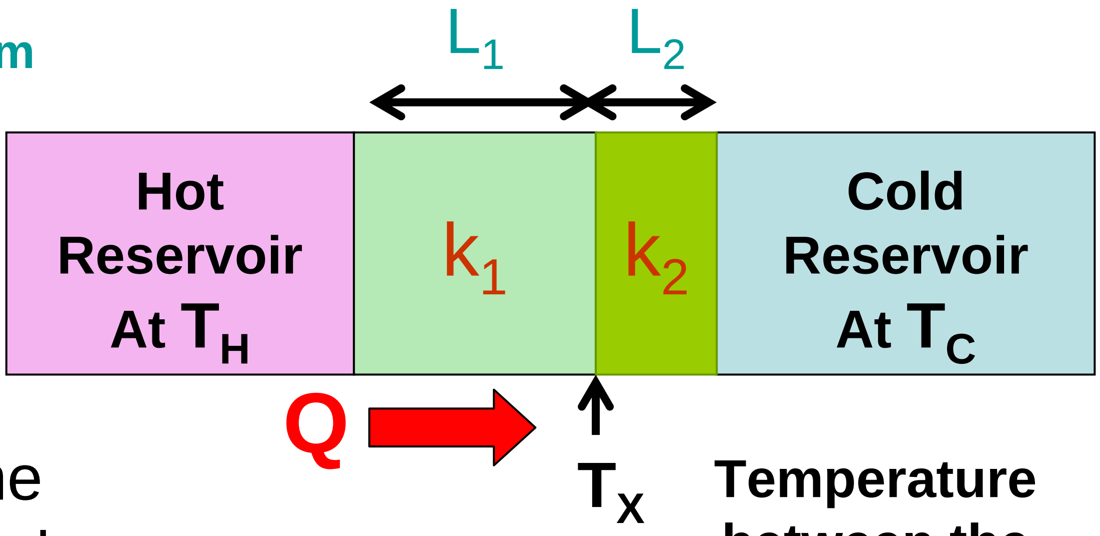
$$R = \frac{L}{k}$$

A slab of a high R-value is a good thermal insulator

19-11 Heat Transfer Mechanism

Conduction

Composite slab



Temperature between the two slabs

In the steady state, the conduction rates through the two materials are equal

$$P_{con} = k_1 A \frac{T_H - T_X}{L_1} = k_2 A \frac{T_X - T_C}{L_2}$$

Eliminate T_X, we get

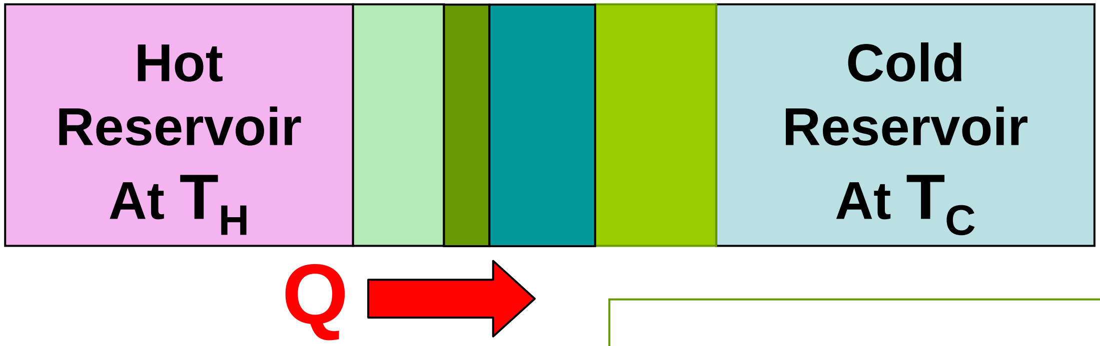
$$P_{con} = A \frac{T_H - T_C}{\frac{L_1}{k_1} + \frac{L_2}{k_2}}$$

19-11 Heat Transfer Mechanism

Conduction

For a slab made of two materials

$$P_{con} = A \frac{T_H - T_C}{\frac{L_1}{k_1} + \frac{L_2}{k_2}}$$



Hot Reservoir At T_H

Cold Reservoir At T_C

Q

For a slab made of number n of materials

$$P_{con} = A \frac{T_H - T_C}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + \ldots + \frac{L_n}{k_n}}$$

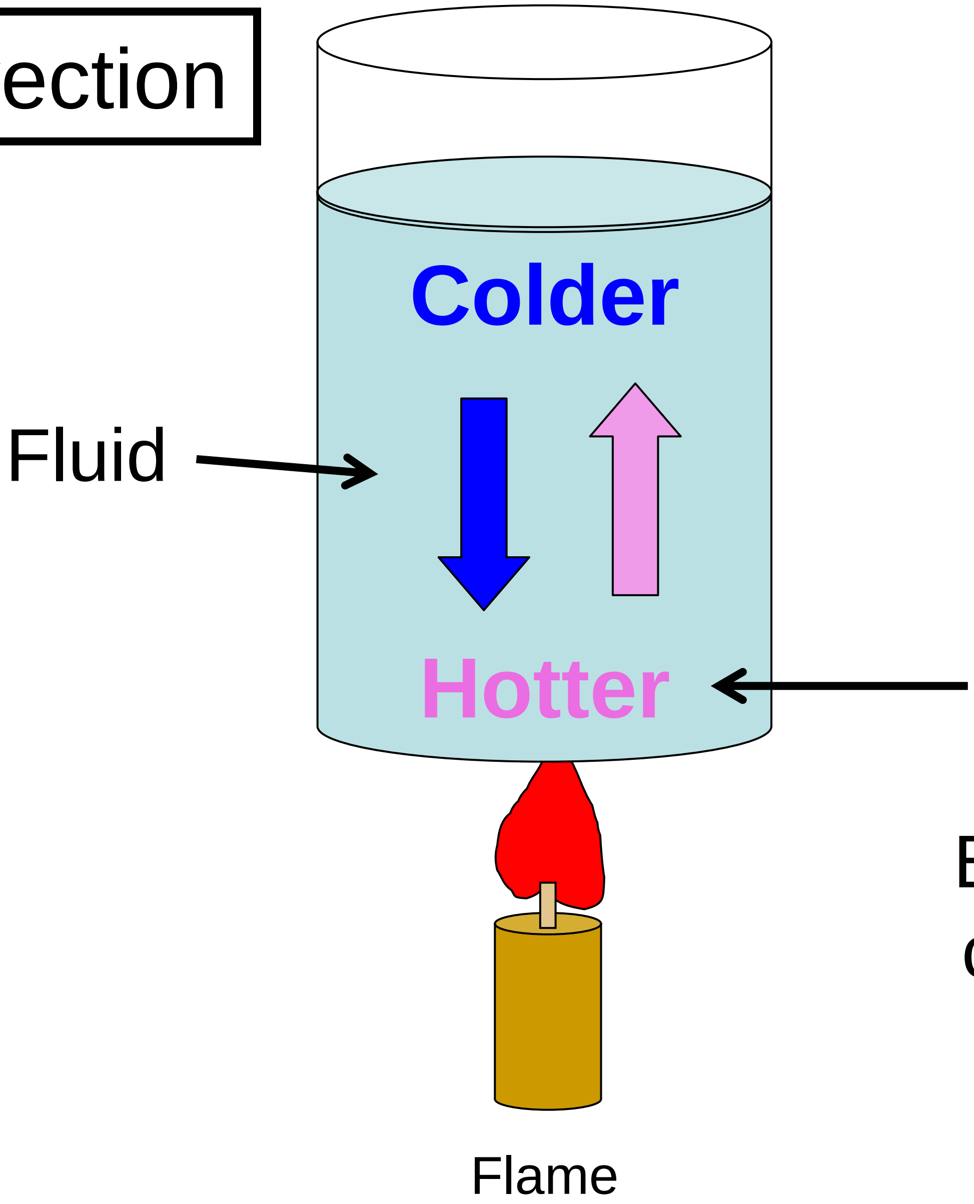
19-11 Heat Transfer Mechanism

Conduction

Check point 7

19-11 Heat Transfer Mechanism

Convection



Colder

Fluid

Hotter

Flame

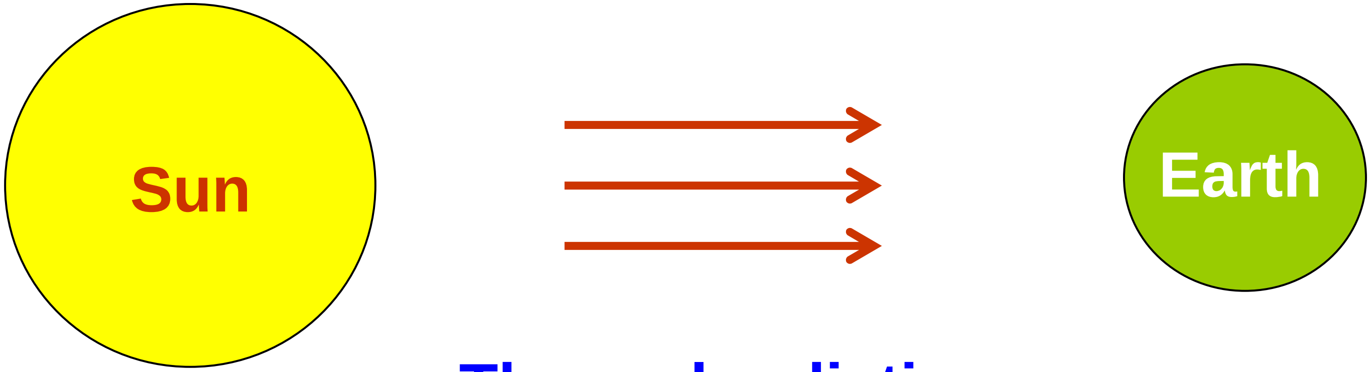
Expansion

Lower density

Buoyant forces
cause it to rise

19-11 Heat Transfer Mechanism

Radiation

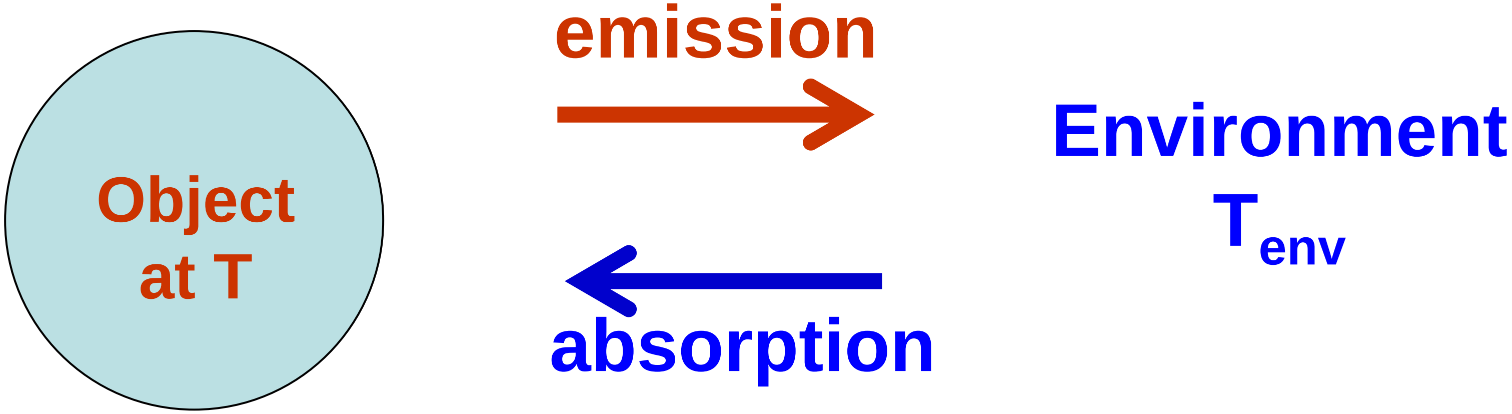


Thermal radiation
(Electromagnetic waves)

No medium required
(Travel through vacuum)

19-11 Heat Transfer Mechanism

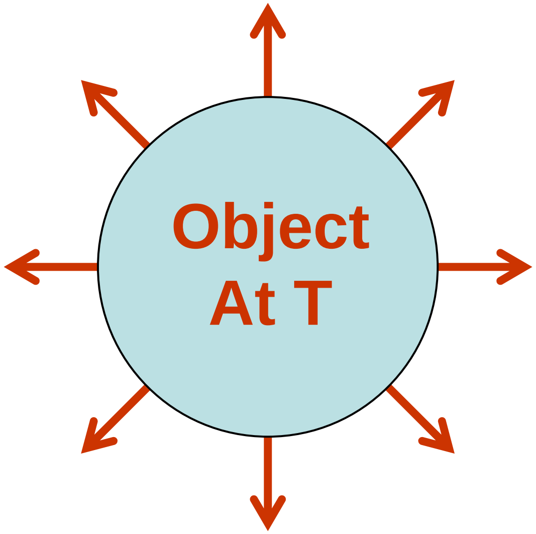
Radiation



Any object emits and absorbs thermal radiation

19-11 Heat Transfer Mechanism

Radiation



Rate at which an object emits thermal radiation

Emissivity of the object's surface

$$P_{rad} = \sigma \varepsilon A T^4$$

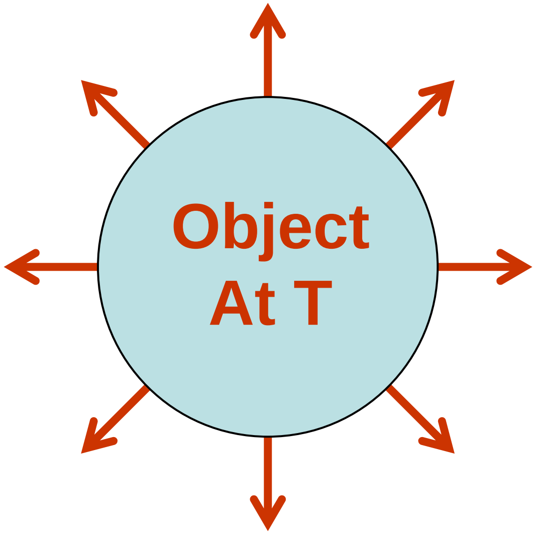
Stefan-Boltzmann constant
$5.67\times10^{-8}\ \mathrm{W/m^2{\cdot}K^4}$

The object's surface area

Temperature of the object's surface **in Kelvins**

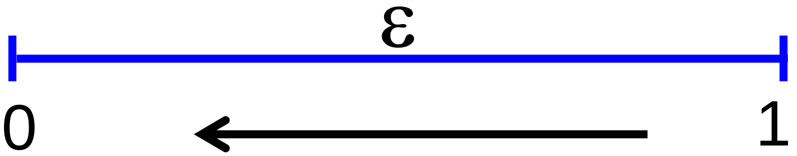
19-11 Heat Transfer Mechanism

Radiation



Emissivity
Value from 0 to 1
Depends on the composition of the surface

$$P_{rad} = \sigma \varepsilon A T^4$$



White
Shiny

Black body radiator
(ideal)

19-11 Heat Transfer Mechanism

Radiation

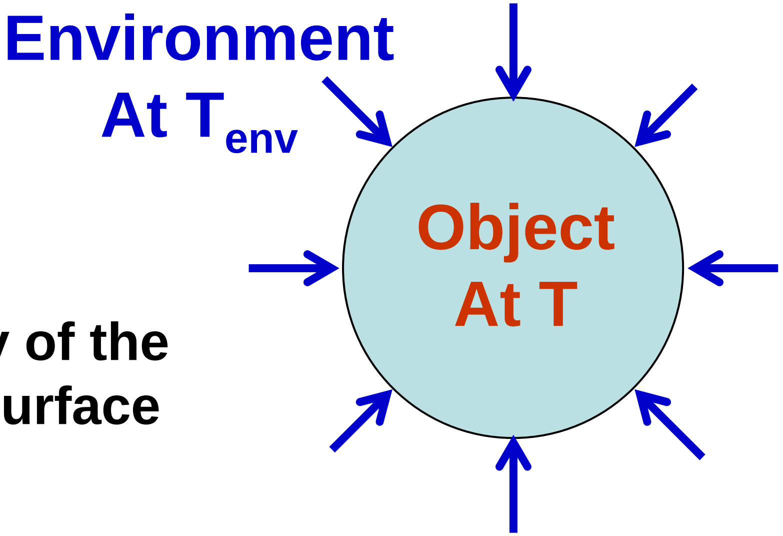
Every object
whose temperature is above 0 K
emits thermal radiation

$$\boxed{P_{rad} = \sigma \varepsilon A T^4}$$

in Kelvins

19-11 Heat Transfer Mechanism

Radiation



Rate at which an object absorbs thermal radiation from its environment

Emissivity of the object's surface

$$P_{abs} = \sigma \varepsilon A T_{env}^4$$

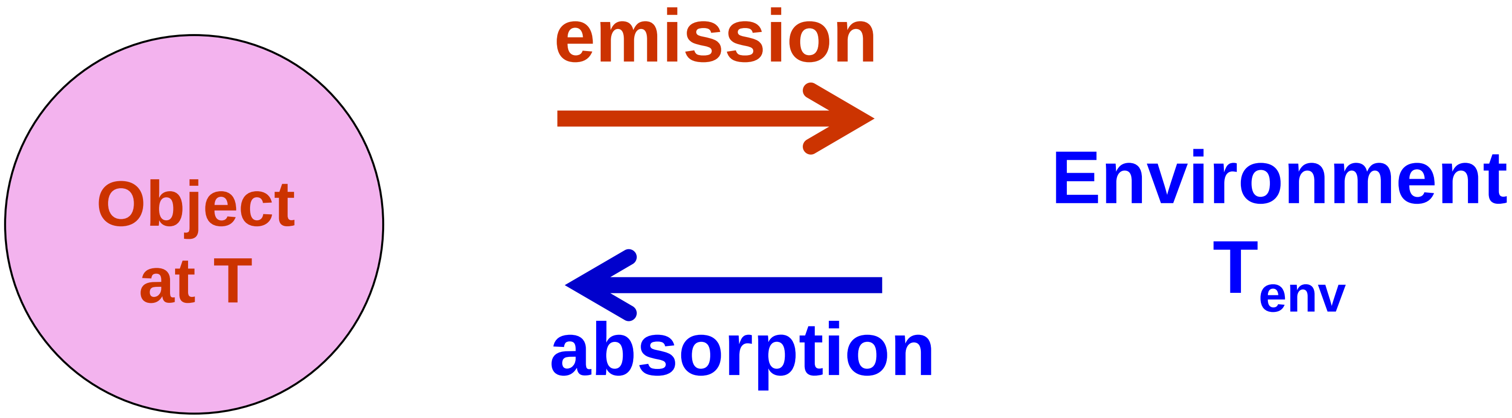
Stefan-Boltzmann constant
5.67×10^{-8} W/m^2·K^4

The object's surface area

Temperature of the object's environment in Kelvins

19-11 Heat Transfer Mechanism

Radiation



Net rate P_{net} of energy exchange due thermal radiation

$$P_{net} = P_{abs} - P_{rad} = \sigma\varepsilon A(T_{env}^4 - T^4)$$

19-11 Heat Transfer Mechanism

Sample Problem 19-6

In steady state, The conduction rates through all layers are the same

$$P_a = P_d$$

$$k_a A \frac{T_1-T_2}{L_a} = k_d A \frac{T_4-T_5}{L_d}$$

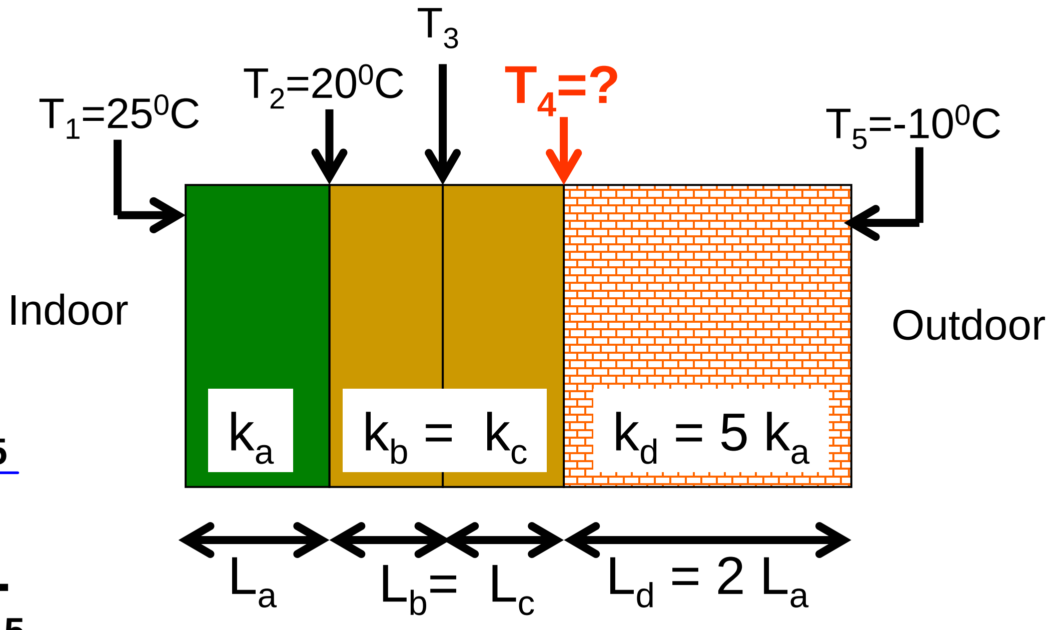
$$\cancel{k_a}\cancel{A}\frac{T_1-T_2}{\cancel{L_a}} = 5\cancel{k_a}\cancel{A}\frac{T_4-T_5}{2\cancel{L_a}}$$

$$T_1-T_2 = \frac{5}{2}(T_4-T_5)$$

$$25^0C-20^0C = \frac{5}{2}(T_4-(-10^0C))$$

$$T_4 = -8^0C$$

Steady State



Four-Layer wall