Classical Physics

- at end of the 19th century:

  - Mechanics - Newton's Laws
  - Electromagnetism - Maxwell's Eqns
  - Optics - Geometric (particles) vs. Physical (waves)
  - Thermodynamics - Four Laws (0-3)
  - Gas Laws - Kinetic Theory

- overlaps often led to important discoveries:

  - Maxwell's Eqns → EM radiation (optics)

  - Newton's laws / kinetic theory → microscopic/atomic description of macroscopic gas laws

- around 1900, Theoretical problems:

1) What is EM medium?
   → Relativity
2) Blackbody Radiation
   → Quantum Physics

- Experimental discoveries:

1895 X-rays

1896 Radioactivity

1897 The electron

Quantum Physics

Relativity

Atomic Physics

Nuclear Physics

Particle Physics

But first...

Heat and Thermodynamics

- study of Thermal Energy of systems

Temperature: a measure of thermal energy, units of Kelvins

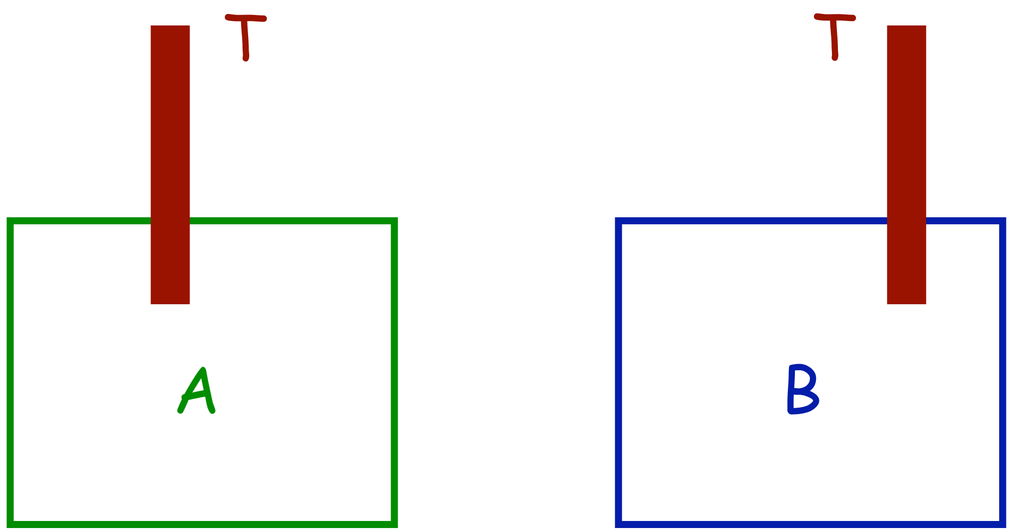
Room Temp ~ 290 K

Temperature of an object is measured by the change in some physical property.

Measuring device is called a thermometer.

Zeroth Law of Thermodynamics

If bodies A and B are each in thermal equilibrium with a third body T, then they are in thermal equilibrium with each other.



Thermal equilibrium: all measureable properties unchanging.

Objects in thermal equilibrium are at the same temperature.

Temperature Scales

- Daniel Fahrenheit (1686-1736)
  - 0°F = mixture of ice, water, salt
  - 100°F = Human body temp (~98.6°F)

- Anders Celsius (1701-1744)
  - 0°C = Freezing point of H_2O
  - 100°C = Boiling point of H_2O

- Lord Kelvin (1824-1907)

H_2O boil : 100°C = 212°F = 373 K

H_2O freeze : 0°C = 32°F = 273 K

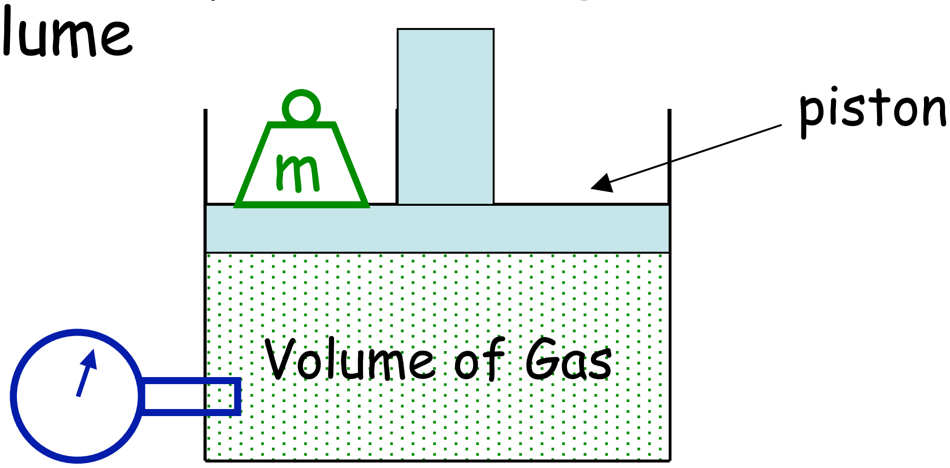
Absolute zero : -273°C = -460°F = 0 K

$T_C = T_K - 273.15$

$T_F = (9/5)T_C + 32$

Constant-Volume Gas Thermometer

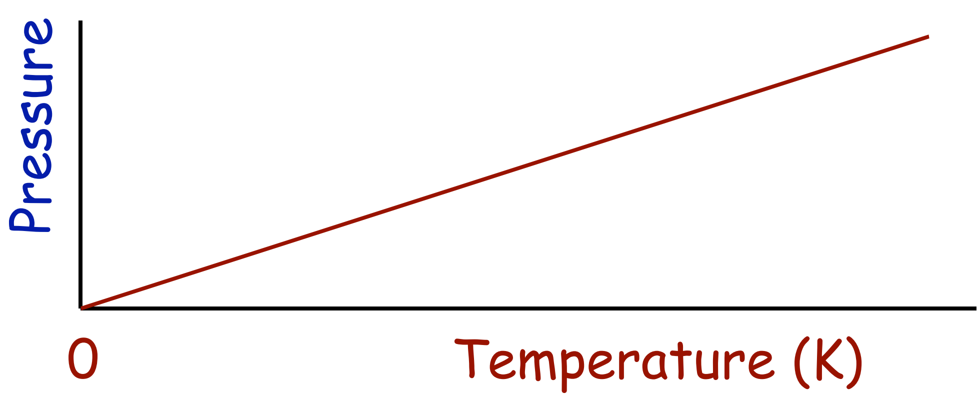
- measure pressure of gas at fixed volume



Pressure = Force/Area (N/m^2=Pa) (Pascals)

1 atm = 1.01x10^5 Pa = 14.7 lb/in^2
= 760 mm of Hg = 760 torr

T P at fixed V



Ideal-Gas Temperature

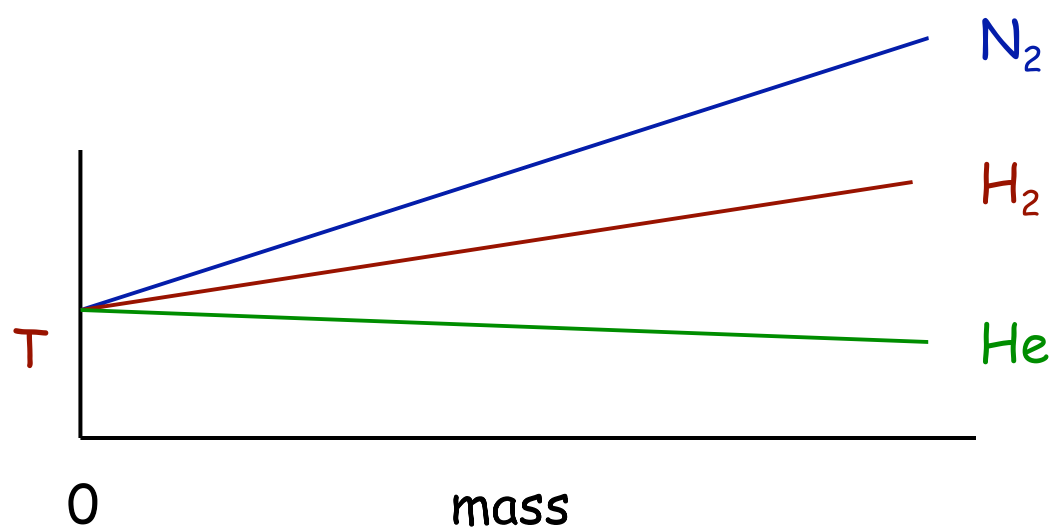
T_k = (constant) x P   at fixed V

-Need one point:
  Triple point of H_2O
  (ice/water/steam coexist)

T_3 = 273.16 K

-Problem: different gases give different T

But as mass of gas reduced ($m \to 0$)
and $P_3 \to 0$, they agree
(approach "ideal" gas)

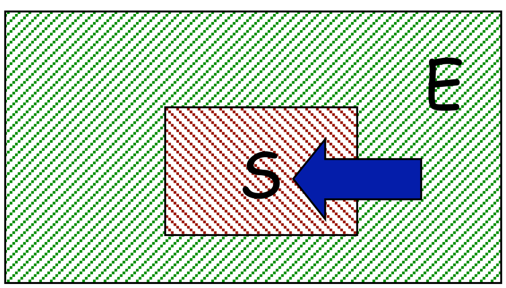


Temperature and Heat

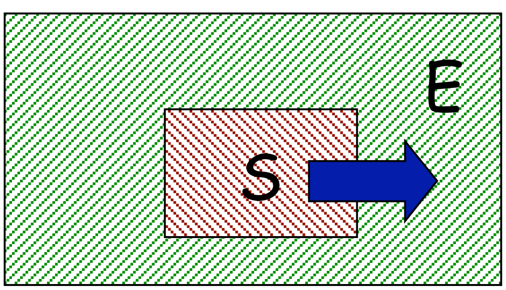
If system S and environment E are
At different temperatures:

Energy will transfer until their temperatures become equal.

The transferred energy is called Heat (symbol Q).



$T_E > T_S$, $Q > 0$
Heat absorbed by S



$T_S > T_E$, $Q < 0$
Heat lost by S

Defn: Require ΔQ = 1 calorie
to raise 1 gm of H_2O by $\Delta T = 1°C$.

1 calorie = 4.186 joules
(heat is a form of energy)

Specific Heat

Amount of heat needed to raise the temperature of m grams of a substance by ΔT is

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

where c is the specific heat (cals/g·°C)

Specific heat of water = 1 cal/g·°C
= 4186 J/kg·K

Molar Specific Heat

Can specify amount of substance in moles:

1 mole = 6.02×10^{23} units
= N_A units (Avogadro's number)

(1 mole of *Al* = 6.02×10^{23} atoms
1 mole of CO_2 = 6.02×10^{23} molecules)

The mass of a substance (in grams) is

$m = n\,A$

where n = (# moles) and
A is the atomic (molecular) weight of the substance.

1 mole of Carbon-12 has m = 12 grams.

Some Examples:

Element	Spec. Heat (J/kg·K)	A	Mol. Sp. Ht. (J/Mole·K)
Lead	128	207	26.5
Tungsten	134	184	24.8
Silver	236	108	25.5
Copper	386	63.5	24.5
Aluminum	900	27	24.4

Note the relative consistency

$$\Delta Q = n\, C\, \Delta T$$

Heats of Transformation

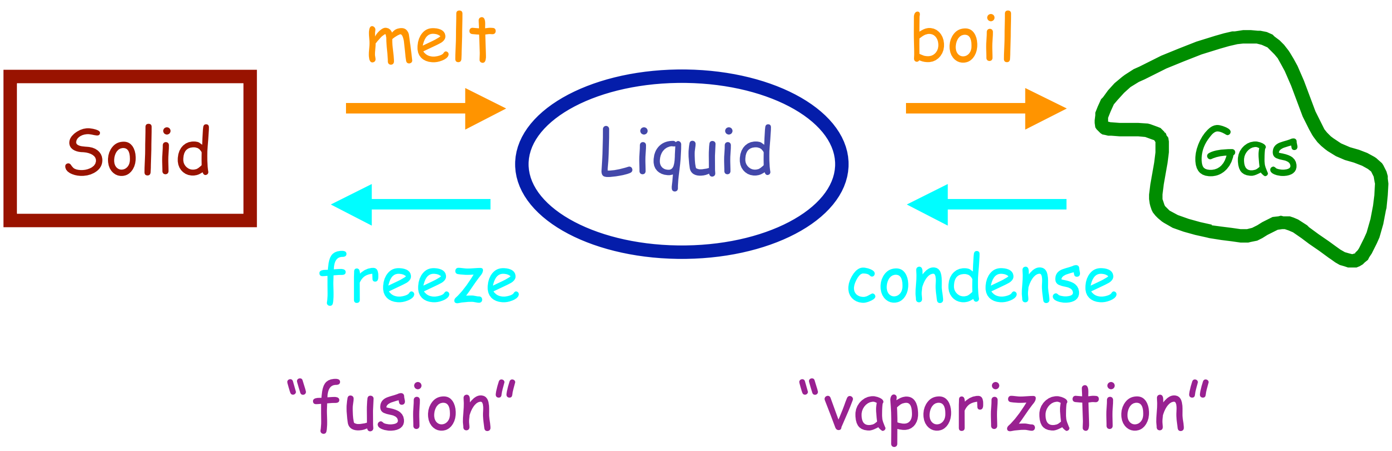
Heat may also change the phase (or state) of a substance (at constant T).

Matter exists in 3 common states:

- Solid

- Liquid

- Gas (or vapor)



Requires energy

Releases energy

Amount of energy/unit mass is

Heat of transformation, L.

e.g. for water:

Heat of fusion

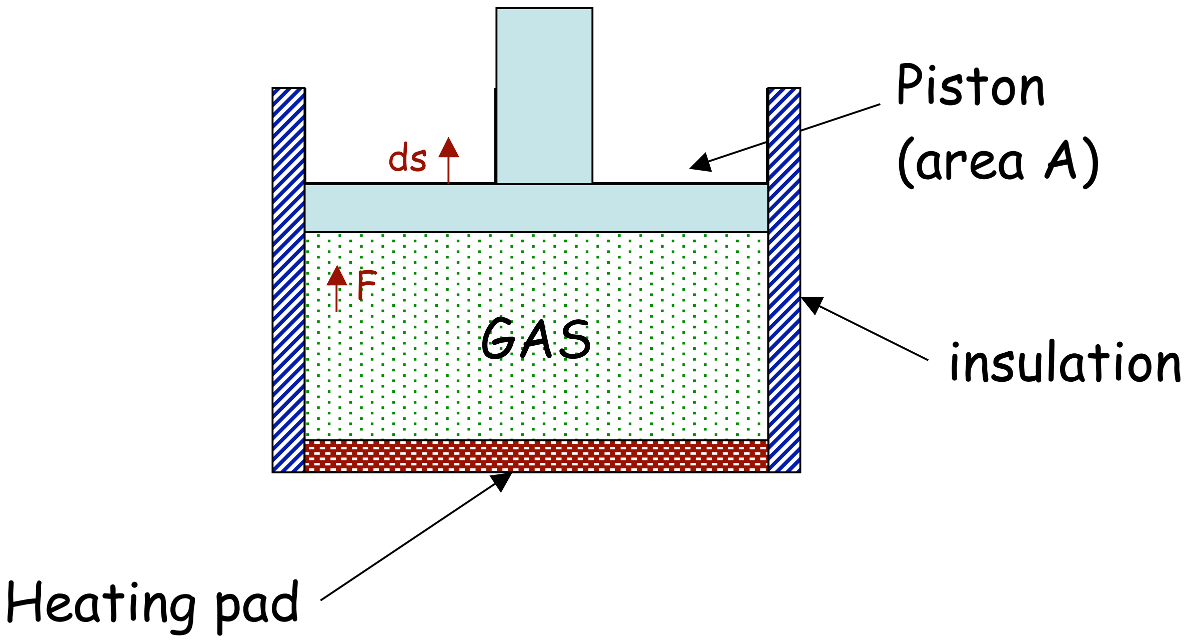
L_F = 79.5 cal/g = 333 kJ/kg = 6.01 kJ/mole

Heat of vaporization

L_V = 539 cal/g = 2256 kJ/kg = 40.7 kJ/mole

Heat and Work

Consider this system:



Pressure = Force/Area   ($P=F/A$)

If piston moves ds, then work done by the gas:

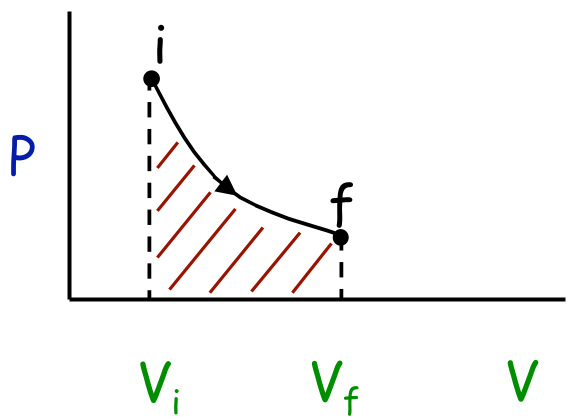
$dW = F\,ds = P\,A\,ds = P\,dV$

Total work done by the gas in moving from V_i to V_f :

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

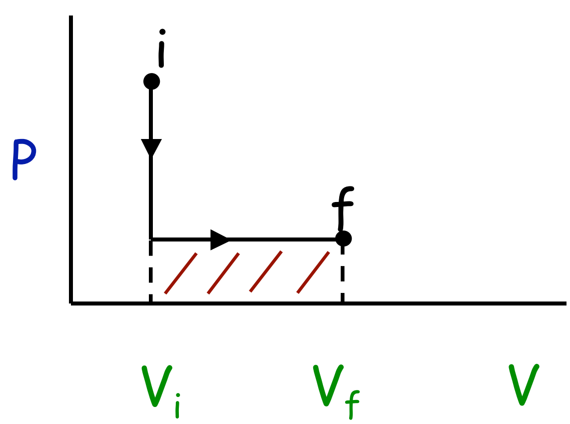
P-V Diagrams

Study effects of heat added/work done by plotting P vs V of gas:

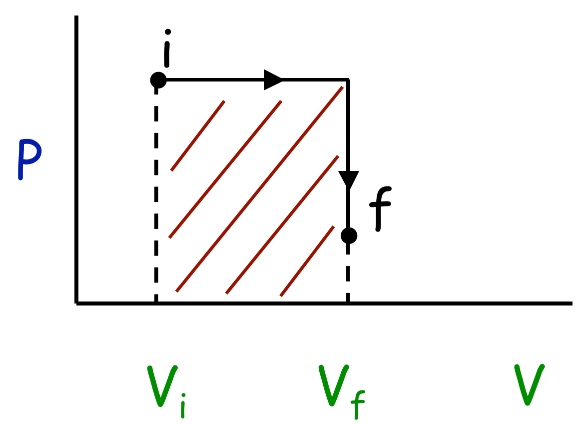


The area under the curve is the work done.

The work done depends on the specific path from i to f.

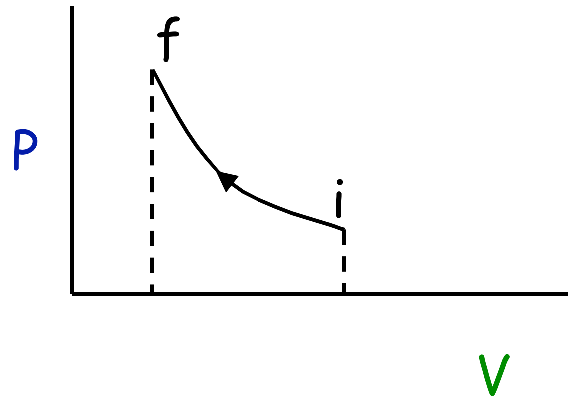


A



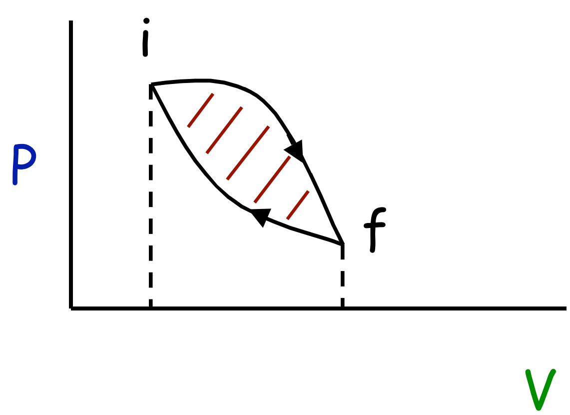
B

Thermodynamic Cycles

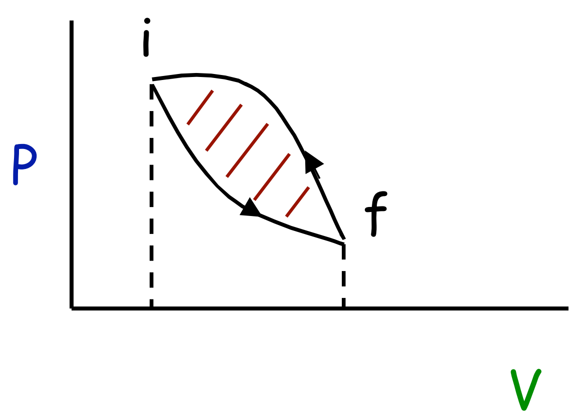


If volume decreases, the work done (by the gas) is negative.

If we go from i□ f and back to i, the net work done by the gas is the area inside the curve.



+ work



- work

First Law of Thermodynamics

Heat ΔQ added to the system can have two effects:

- Increase the internal energy of the system

- Cause the gas to do work

Conservation of Energy says:

$$\Delta Q = \Delta U + \Delta W$$

where

U is the internal energy of the system.

⇒ 1st Law of Thermodynamics.

State Functions

A property of the state of the system is often called a "State Function".

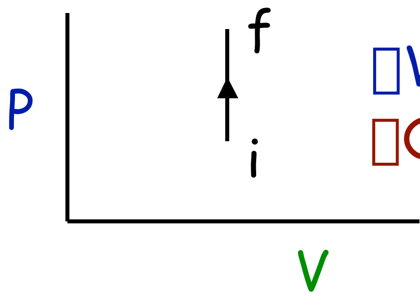
P, V, and T are state functions.
So is U (the internal energy).

Heat and Work are not.
They are path-dependent, i.e. they depend on how we go from i to f.

However the combination
$\Delta Q - \Delta W = \Delta U$ does not depend on the path.

Various System Changes

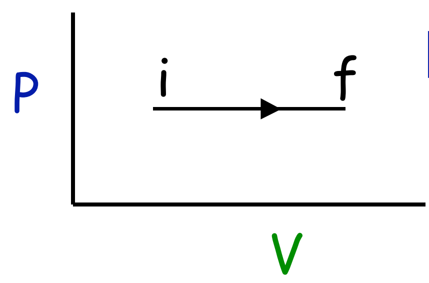
Constant Volume
(isochoric)



$\Delta W=0$

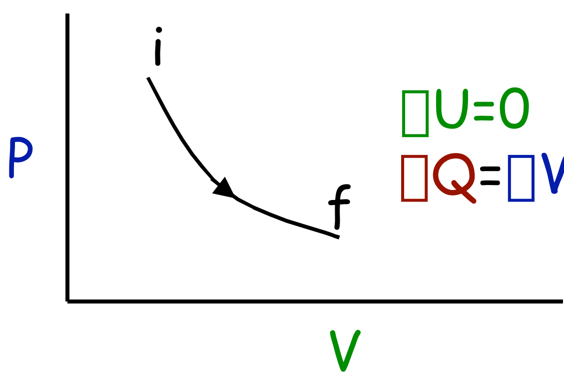
$\Delta Q=\Delta U$

Constant Pressure
(isobaric)



$\Delta W=P\Delta V$

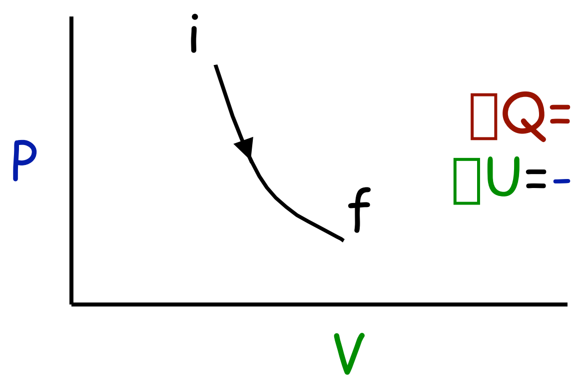
Constant Temp
(isothermal)



$\Delta U=0$

$\Delta Q=\Delta W$

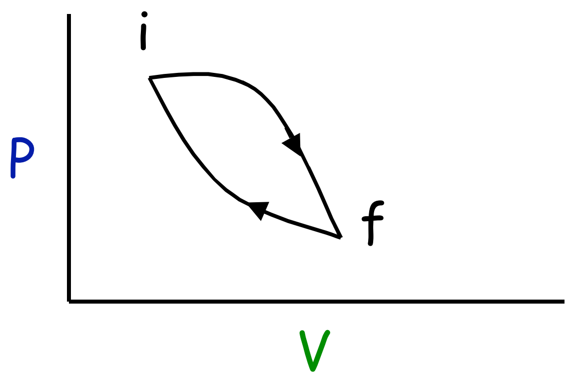
Constant Heat
(adiabatic)



$\Delta Q=0$

$\Delta U=-\Delta W$

Cyclical Process
(returns to original state)



$\Delta U=0$

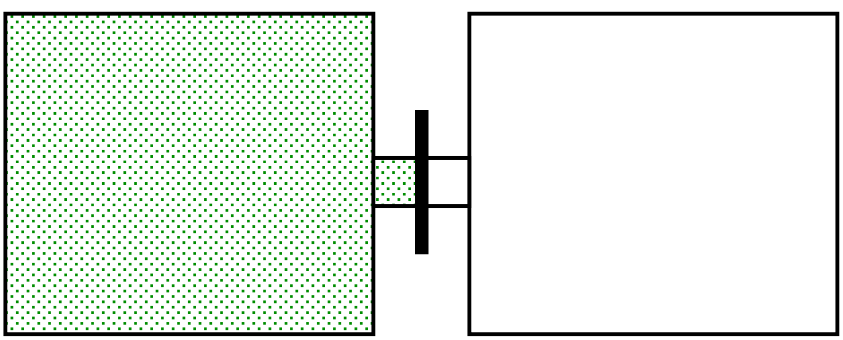
$\Delta Q=\Delta W$

All previous cases are "quasi-static":

Change occurs slow enough that thermal equilibrium can be considered true at all times.

A non-quasi-static process:

Adiabatic, free expansion:



$\Delta Q = 0$ (adiabatic)

$\Delta W = 0$ (nothing to work against)

$\Rightarrow \Delta U = 0$

Heat Transfer Mechanisms

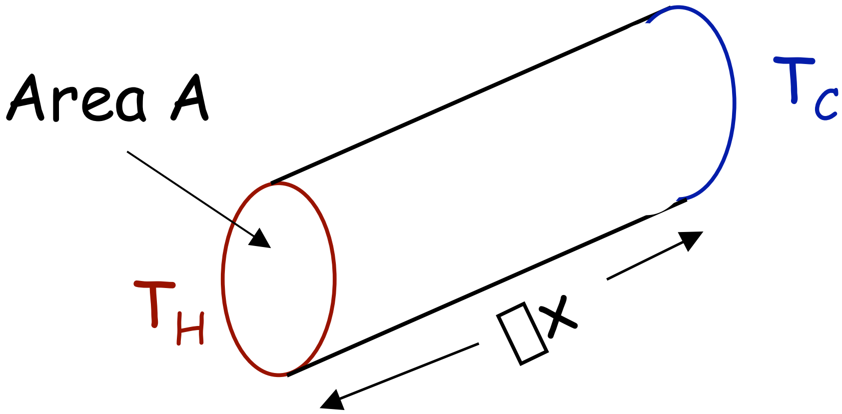
How does heat exchange occur?

- Conduction
- Convection
- Radiation

Conduction

- Occurs in systems where atoms stay in a fixed region.
- Heat energy causes them to move, rotate, and/or vibrate.
- Energy is transferred to adjacent atoms by interactions/collisions.

Energy moves, not the atoms



Heat conduction rate is

$$P_{cond} = \Delta Q/\Delta t = \kappa A \,\Delta T/\Delta x$$

- $\Delta T/\Delta x = (T_H - T_C)/\Delta x$ is the Temperature gradient.
- P_{cond} is the Energy transferred per time (SI units: Watts), sometimes called thermal current, I.
- κ is the <u>Thermal Conductivity</u> (SI units: Watts/m·K).

Some Thermal Conductivities

Silver	428	W/m•K
Copper	402	
Aluminum	235	
Lead	35	
Stainless Steel	14	
Hydrogen	0.18	
Helium	0.15	
Dry Air	0.026	
Window Glass	1.0	
White Pine	0.11	
Fiberglass	0.048	
Polyurethane Foam	0.024	

Copper
401

Brass
~70

Aluminum
235

Nickel
~ 92

German Silver
(Copper/Zinc/Nickel)
~ 42

Iron
~ 84

Using the notation I for P_{cond},

$$\Delta T = I \, \Delta x / (kA)$$

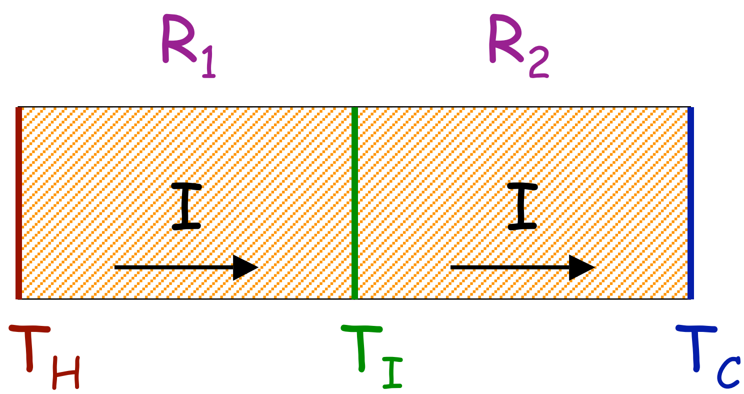
or

$$\Delta T = I \, R$$

where $R = \Delta x / (kA)$ is
<u>the thermal resistance.</u>

Note analogy with Ohm's Law for electricity.

Two or more conductors (or insulators) in series:



Steady state □ thermal current is same through both slabs

$$T_H - T_I = I\,R_1$$
$$T_I - T_C = I\,R_2$$

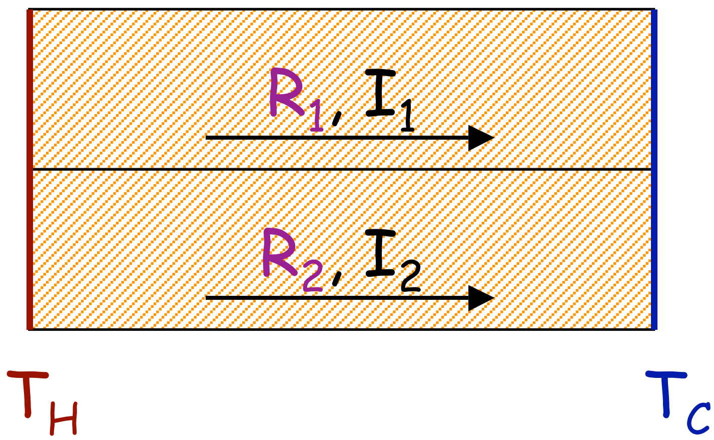
$$T_H - T_C = I\,(R_1 + R_2) = I\,R_{equiv}$$

where

$$R_{equiv} = R_1 + R_2 + \ldots$$

(like resistances in series)

Conductors in parallel:
(multiple paths for heat flow)



$T_H - T_C = \Delta T$: same for all paths
but current flows (I) are different.

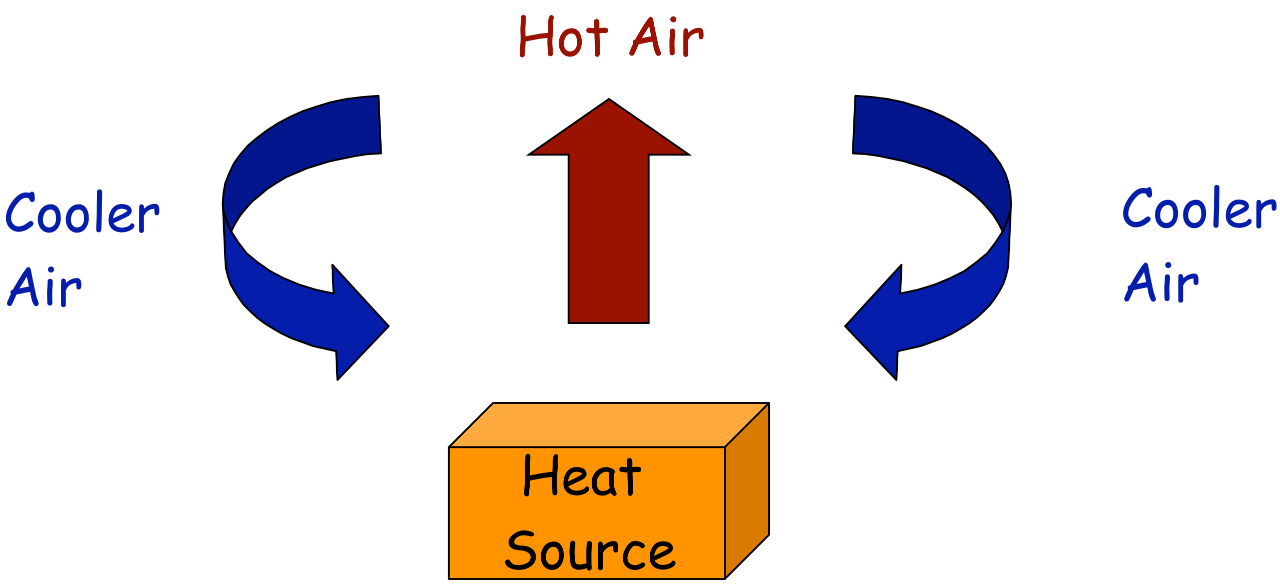
$$
\begin{aligned}
I_{total} &= I_1 + I_2 + \ldots \\
&= \Delta T/R_1 + \Delta T/R_2 + \ldots \\
&= \Delta T\,(1/R_1 + 1/R_2 + \ldots) \\
&= \Delta T/R_{equiv}
\end{aligned}
$$

with

$$1/R_{equiv} = 1/R_1 + 1/R_2 + \ldots$$

(like resistances in parallel)

Convection



•Occurs in fluid systems.
The energy flows along with the medium.

•Fluid near heat source becomes hot, expands, and rises.
Surrounding cooler fluid takes its place. Etc.

Radiation

Here the energy is carried by electromagnetic waves. Called Thermal Radiation.

The Rate at which an object radiates is given by the Stefan-Boltzman Law:

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

where

P_{rad} : Power radiated in Watts
A : Area of emitter
T : Temperature of emitter in K
σ : Universal constant
(S-B's constant)
$\sigma = 5.6703 \times 10^{-8}$ W/(m^{2}K^4)
ϵ : the emissivity of the emitter
($0 < \epsilon < 1$, depending on the composition of the surface)

The rate an object absorbs thermal radiation is given by the same formula:

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

except that now T_{env} is the <u>temperature of the enviroment</u>.

The emissivity ε of an object is <u>the same</u> for radiation and absorption.

- Lighter objects reflect more.
  (smaller ε)
- Darker objects absorb more.
  (larger ε)
  They also emit more.

A surface with $\varepsilon = 1$ is called a <u>Blackbody radiator.</u>