EMS717U/EMS717P

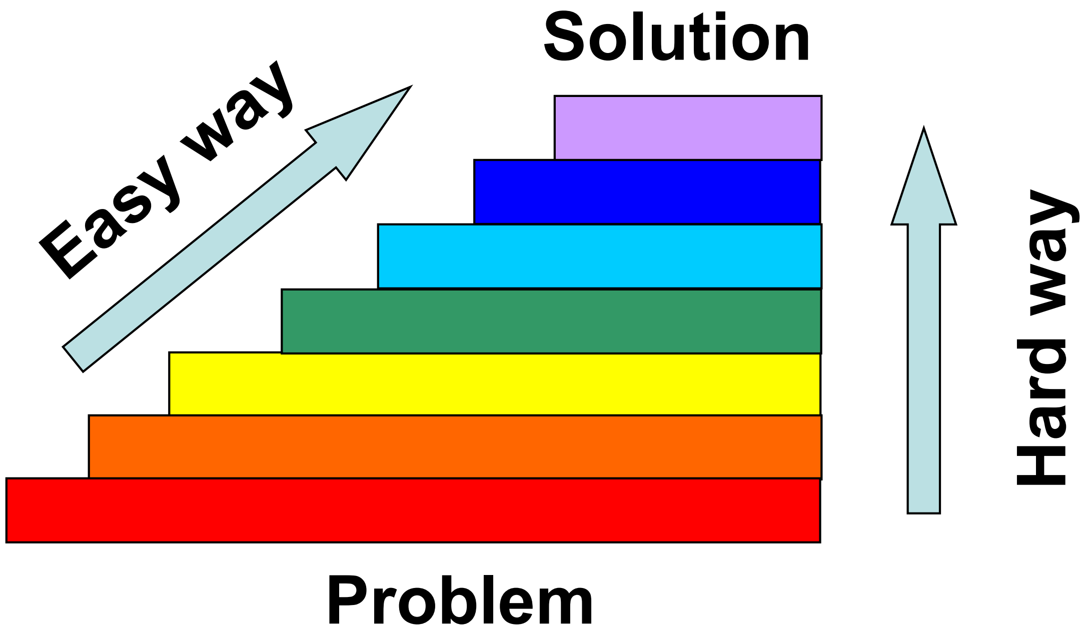
Renewable Energy Sources

Thermodynamics of Energy Conversion - REVISION

Prof. Huasheng Wang

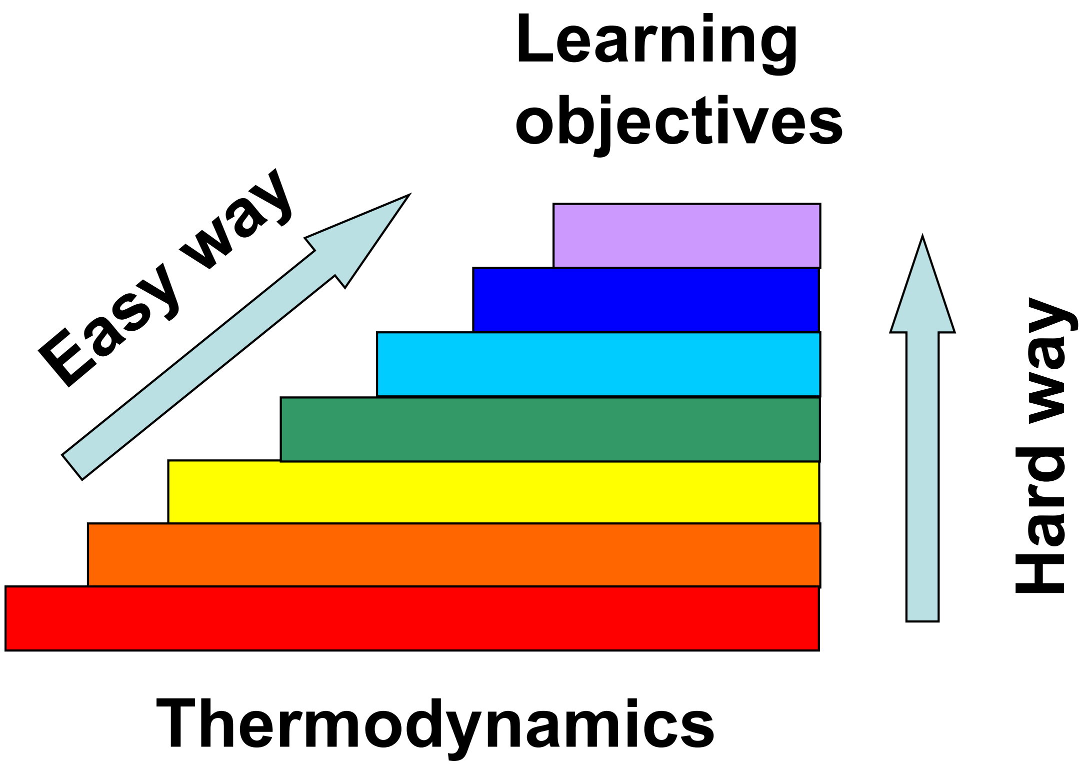
Problem Solving Techniques - 1

- A step-by-step approach



Problem Solving Techniques - 2

- A step-by-step approach



Problem Solving Techniques - 3

- General step-by-step approach

1. Problem statement; info given, to be found, objectives
2. Draw a schematic; indicate relevant info on
3. Assumptions and approximations; simplify, justify
4. Physical laws; apply relevant laws and principles
5. Properties; property relations, tables, property source
6. Calculations; units, significant number ("do not copy")
7. Reasoning, verification, and discussion; validity, significance, implications, conclusions, recommendations, limitations,
8. Neatness, organization, completeness, visual appearance

Problem Solving Techniques - 4

- **Conservation of mass, momentum, energy & electrical charge (the first law of thermodynamics)**

$$\left\{\begin{array}{l}\text{The net gain in} \\ X \text{ by the system}\end{array}\right\} = \left\{\begin{array}{l}\text{The net amount of } X \\ \text{transported into the system}\end{array}\right\}$$

$$+ \left\{\begin{array}{l}\text{The net amount of } X \\ \text{generated by the sytem}\end{array}\right\}$$

$$1+2=3 \qquad a+b=c$$

$$1+2-3=0 \qquad a+b-c=0$$

$$1=3-2 \qquad a=c-b$$

Problem Solving Techniques - 5

- **Balance of entropy (ΔS_{irr})**

$$\begin{Bmatrix}\text{The net gain in} \\ X \text{ by the system}\end{Bmatrix} = \begin{Bmatrix}\text{The net amount of } X \\ \text{transported into the system}\end{Bmatrix}$$

$$+ \begin{Bmatrix}\text{The net amount of } X \\ \text{generated by the sytem}\end{Bmatrix}$$

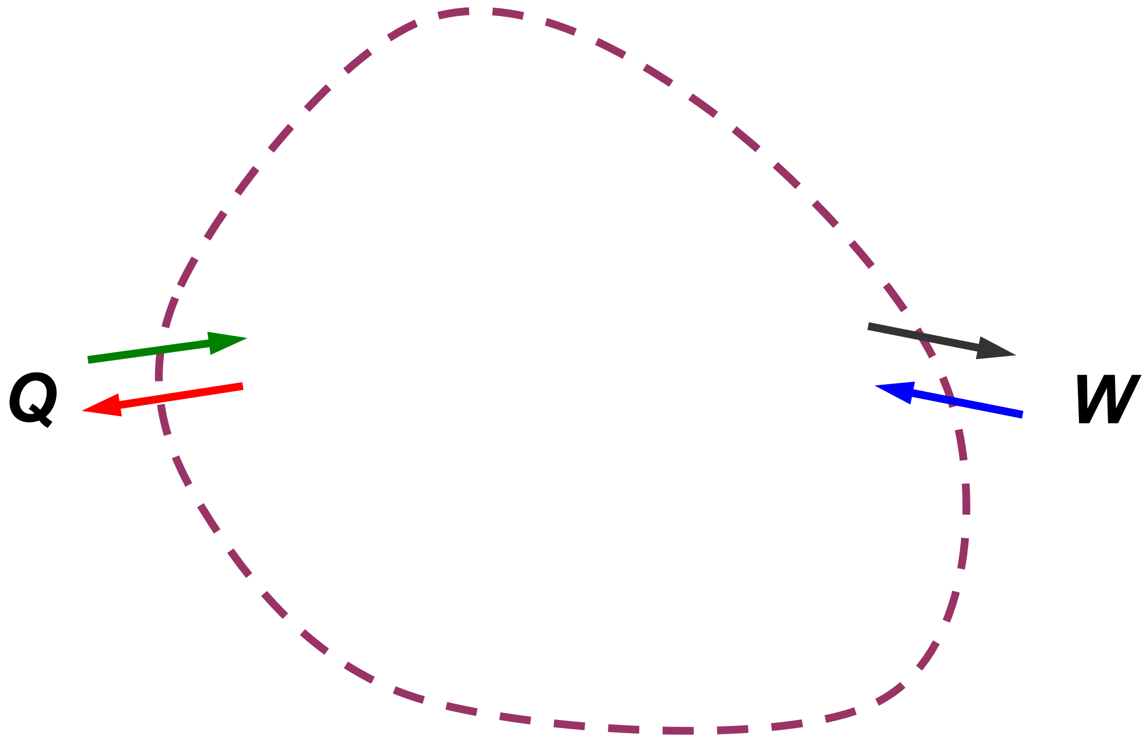
$$a + b = c$$

$$a + b - c = 0$$

$$a = c - b$$

Problem Solving Techniques - 6

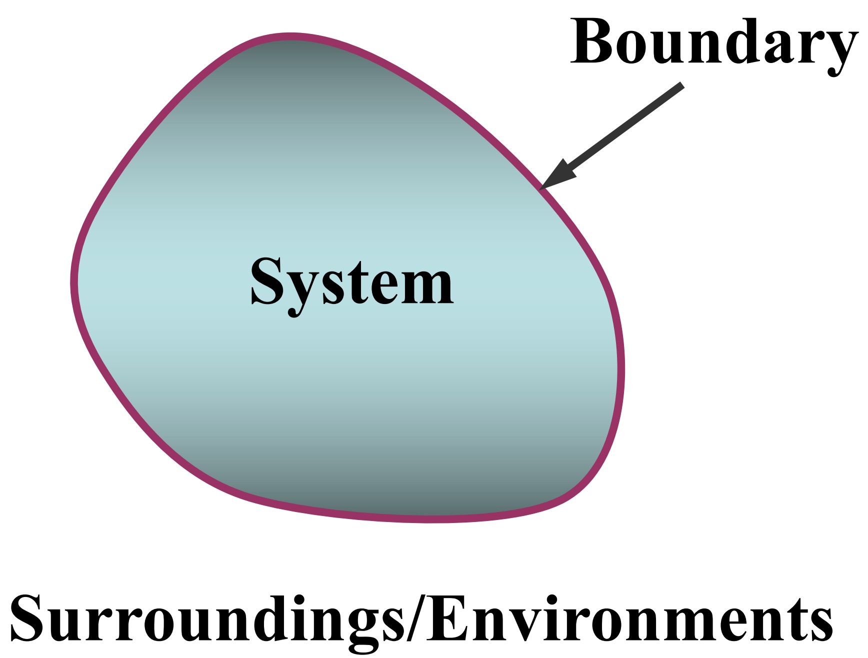
- **Sign "convention"**



Fundamental Concepts - 1

- **Thermodynamic system**

  material, body, amount of fluid, under discussion, identifiable collection of matter



Fundamental Concepts - 2

- **Thermodynamic system**

Surroundings/Environments

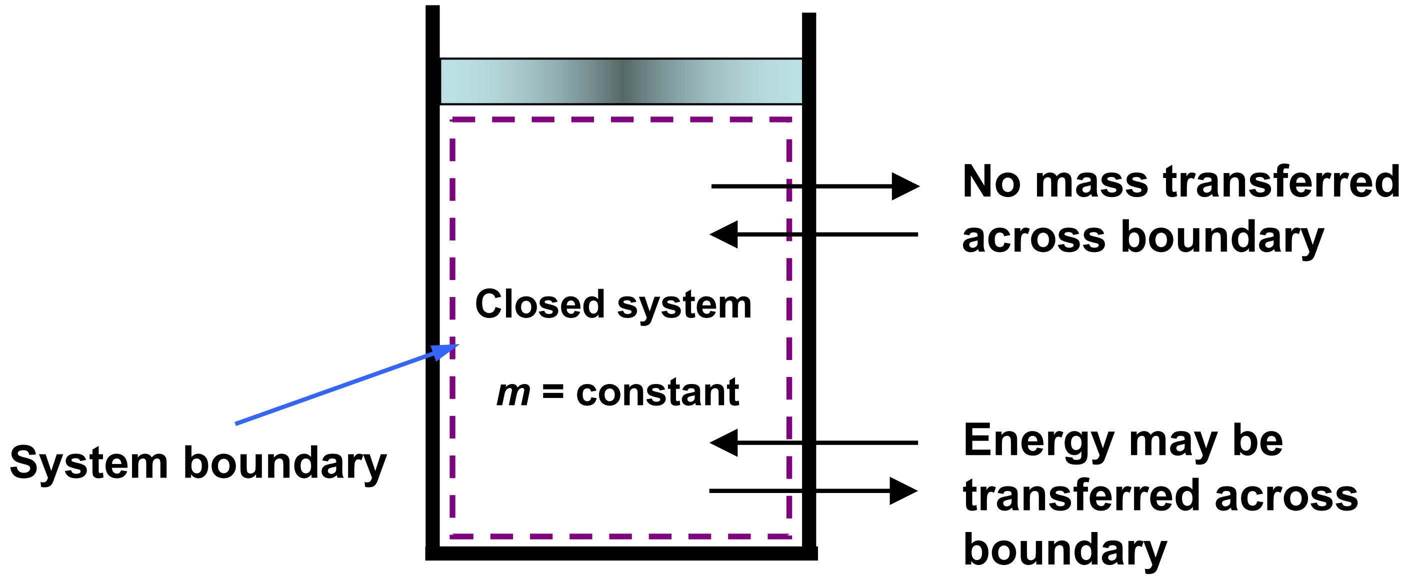
Boundary

- **Fixed and moving**
- **Real and imaginary; work**
- **“Thermal conductor” and adiabatic; heat**
- **Permeable and non-permeable; mass**

Fundamental Concepts - 4

- **Thermodynamic system**

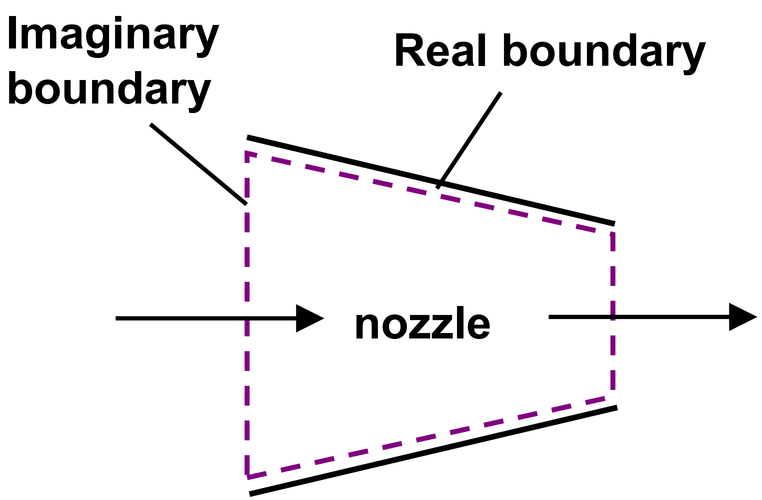
Closed system (control mass)

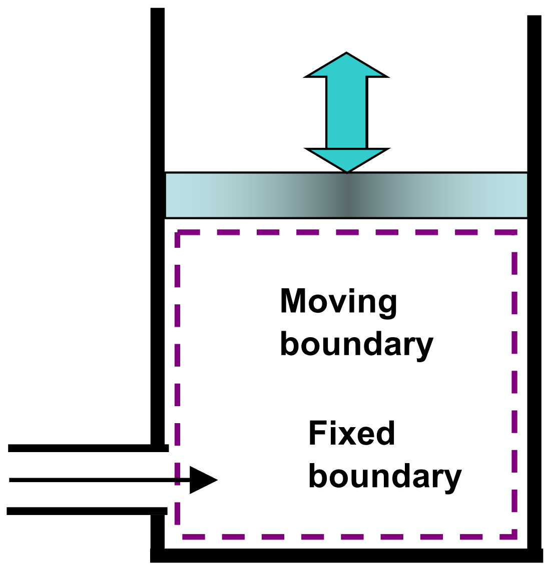


Fundamental Concepts - 5

- **Thermodynamic system**

  Open system (control volume)

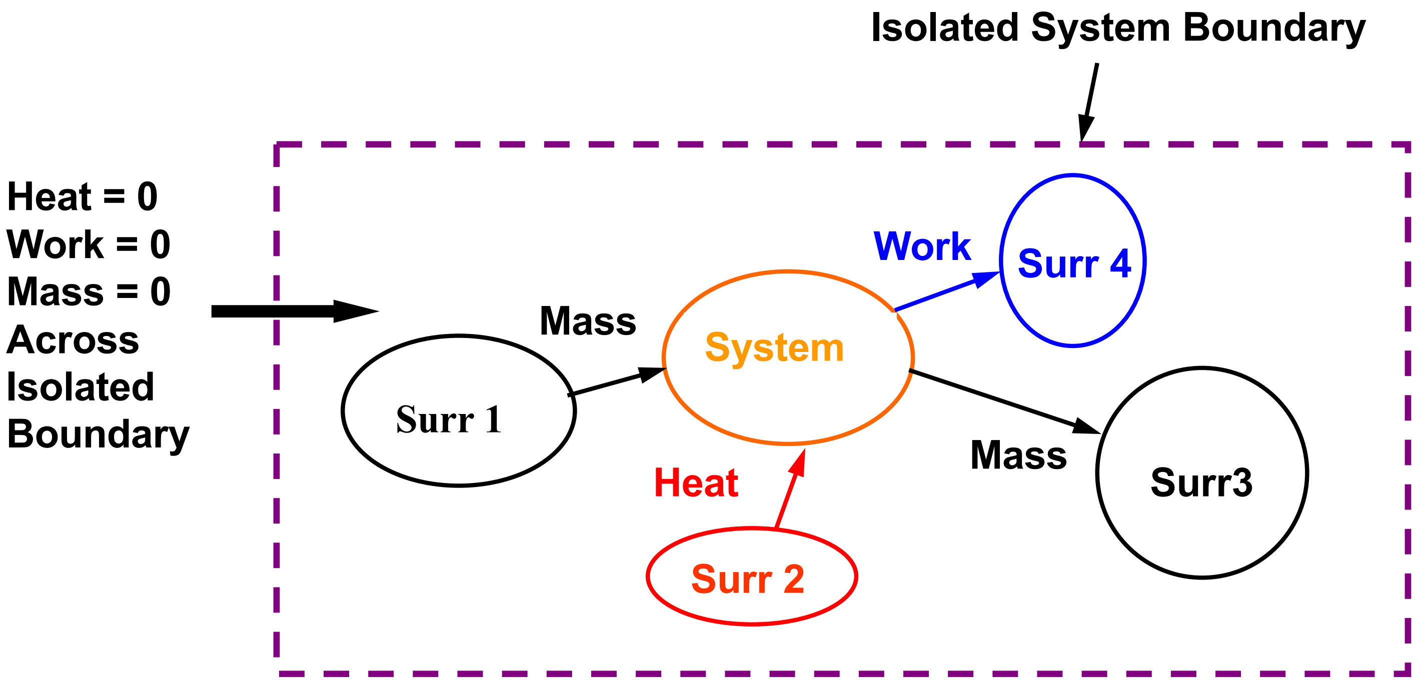




Fundamental Concepts - 6

- **Thermodynamic system**

  Isolated system



Fundamental Concepts - 7

- **Property of a system**

  Characteristic of a system which can be measured

- **Extensive properties**

  mass m, volume V, energy E, entropy S, etc.

- **Intensive properties**

  pressure P, temperature T, specific volume v, etc.

Fundamental Concepts - 8

- **Energy, *E* and entropy, *S***

  - $dE = 0$
  - $dS \geq 0$

For an isolated system the internal energy is constant and the entropy can only increase. Entropy is constant for ideal reversible process

Fundamental concepts - 9

- **Property of a system**

E*, *S*, *V **fundamental thermodynamic properties (extensive)**

$$\left.\begin{matrix} W \\ \\ Q \end{matrix}\right\}$$ **NOT properties**

note symbols

+ ive when energy transfer is to the system

Specific quantity – quantity / mass of system

Specific properties

$v = V / m$, $e = E / m$, $s = S / m$

Other specific quantities

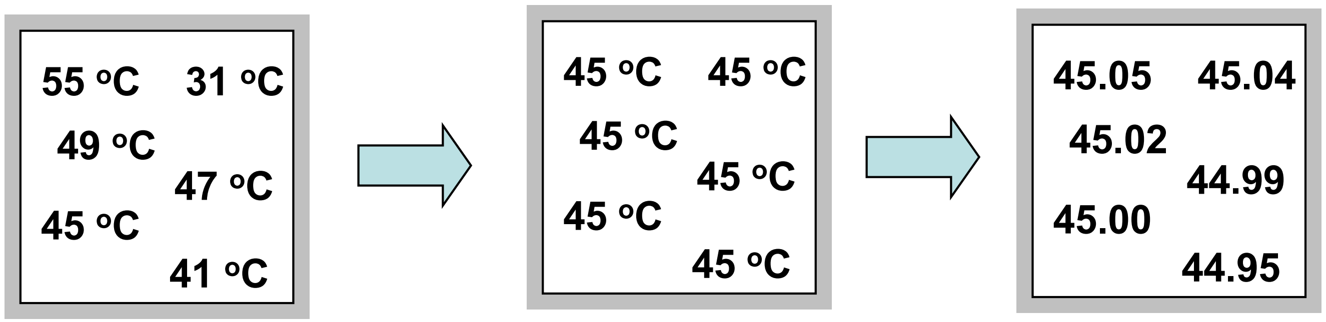
$w = W / m$, $q = Q / m$

Specific force of gravity $m\, g / m = g$

Fundamental Concepts - 10

- **Equilibrium**

  The properties of systems (*“left alone” i.e. isolated*) are observed to attain constant values, i.e. the system comes to equilibrium. Subsystems in equilibrium are themselves in equilibrium



Fundamental Concepts - 11

- **Equilibrium state**

  When all of the properties of a system are constant

  How many independent properties are needed in order to determine a equilibrium state?

Fundamental Concepts - 12

- **Simple fluid**

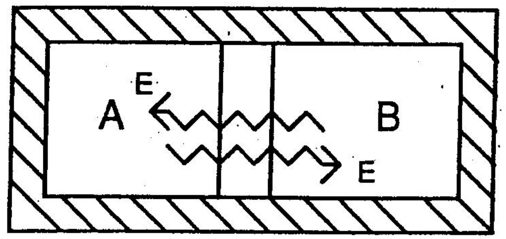
- $\psi(E, S, V) = 0$
- $S = S(E, V)$
- $E = E(S, V)$

- **For unit mass of a simple homogenous fluid**

- $\Phi(e, s, v) = 0$
- $s = s(e, v)$
- $e = e(s, v)$

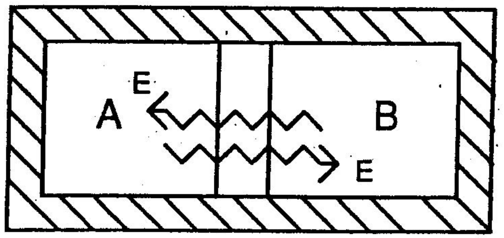
Equilibrium State - 1

- Temperature and pressure
- Consider isolated system shown comprising two subsystems A and B
- A + B isolated; A and B not isolated from each other
- Entropy is extensive so $S = S_A + A_B$
- System is isolated so
- $E_A + E_B$ = constant
- $V_A + V_B$ = constant



Equilibrium State - 2

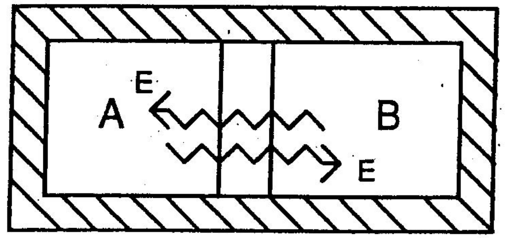
- Temperature and pressure
- (a) Energy may be shared between A and B if the dividing boundary permits energy transfer (thermal conductor).
- (b) Volume may be shared between A and B if the dividing boundary is freely movable.
- The equilibrium state of the isolated system must be an equilibrium state of A and an equilibrium state of B with energy and volume distributed between the two so as to maximize the total entropy



Equilibrium State - 3

- **Temperature and pressure**

- **It may be shown that when (a) is true**



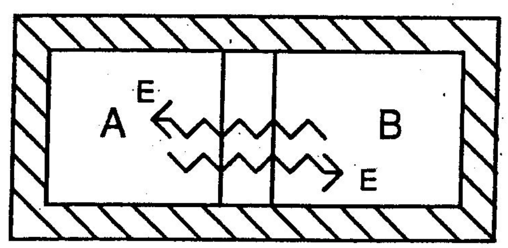
$$\underset{\text{System A}}{(\partial E/\partial S)_V} = \underset{\text{System B}}{(\partial E/\partial S)_V}$$

- **Thermodynamic temperature of a simple fluid system is defined by**

$$T = (\partial E/\partial S)_V = (\partial e/\partial s)_v$$

Equilibrium State - 4

- **Temperature and pressure**
- **It may be shown that when (b) is true**

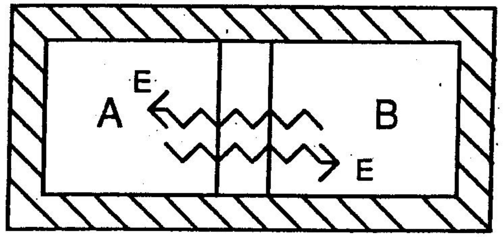


$$\underset{\text{System A}}{(\partial E/\partial V)_S} = \underset{\text{System B}}{(\partial E/\partial V)_S}$$

- **Thermodynamic pressure of a simple fluid system is defined by**

$$P = -(\partial E/\partial V)_S = -(\partial e/\partial v)_s$$

Equilibrium State - 3



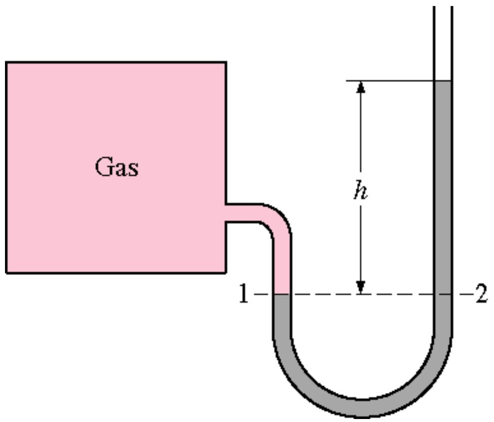
- **Temperature and pressure**
- **So, for equilibrium**
- $T_A = T_B$ **when separating boundary is a "thermal conductor"**
- $P_A = P_B$ **when separating boundary is freely moveable**
- **Driving force**

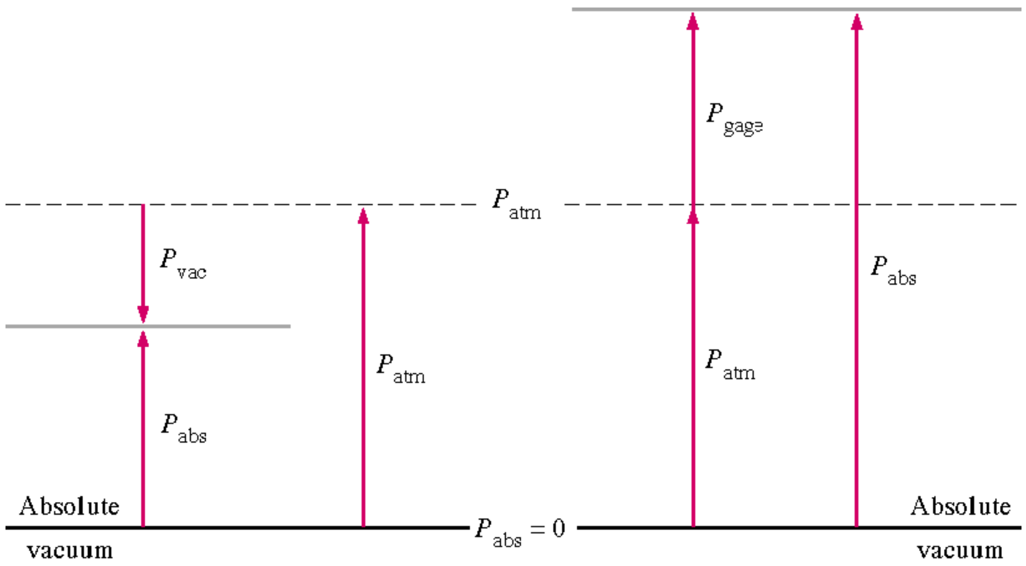
$$E = E(S, V) \qquad dE = \left(\frac{\partial E}{\partial S}\right)_V dS + \left(\frac{\partial E}{\partial V}\right)_S dV$$

$$dE = TdS - PdV \qquad de = Tds - Pdv$$

Equilibrium State - 6

- **Pressure**

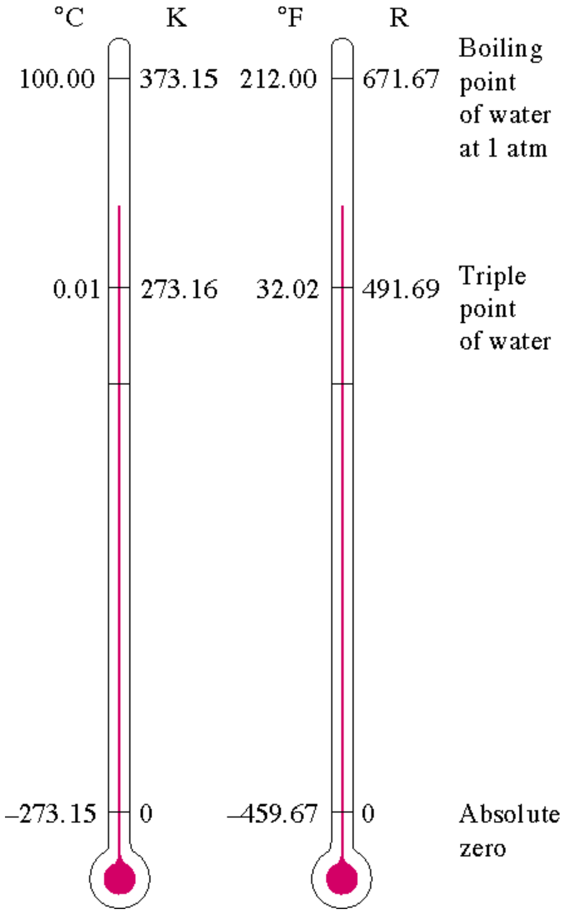


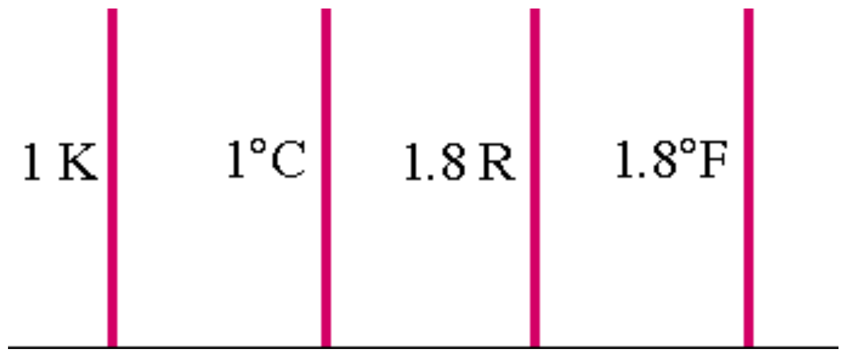


- $P_{abs} = P_{atm} + P_{gauge}$ **(Be careful!)**

Equilibrium State - 7

- **Temperature**





- ***T* = *t* + 273.15**

- ***Absolute temperature* should be used in all thermodynamics calculation.**

Equilibrium State - 8

- **Two-property rule for closed simple fluid system**

For equilibrium states

- $E = E(S, V)$ (1)
- $T = (\partial E/\partial S)_V = T(S, V)$ (2)
- $P = - (\partial E/\partial V)_S = P(S, V)$ (3)

- **Homogeneous closed system**
- $e = e(s, v)$ (1)
- $T = (\partial e/\partial s)_v = T(s, v)$ (2)
- $P = - (\partial e/\partial v)_s = P(s, v)$ (3)

Gibbs Phase Rule

- **Multicomponent, multiphse system**
- $IV = C - PH + 2$

IV – **the number of independent variables**

C – **the number of components (constituents, species)**

PH – **the number of phases present in equilibrium**

Summary – Property rule

- **<u>Closed system (constant mass)</u>**

  State is fixed by any 2 of *E*, *S*, *V*, *P*, *T*, *G*, *H*

- **<u>Homogeneous closed system</u>**

  Intensive *s*tate is fixed by any 2 of *e*, *s*, *v*, *P*, *T*, *g*, *h*

- **<u>Homogeneous phase of pure fluid</u>**

  Intensive *s*tate is fixed by any 2 of *e*, *s*, *v*, *P*, *T*, *g*, *h*

Specific Heat-Capacities

- **Summary**

$$c_v = T\left(\frac{\partial s}{\partial T}\right)_v = \left(\frac{\partial e}{\partial T}\right)_v \qquad c_P = T\left(\frac{\partial s}{\partial T}\right)_P = \left(\frac{\partial h}{\partial T}\right)_P$$

- If c_v can be taken constant between T_1 and T_2, then, for a quasi-equilibrium constant volume process

$$q = c_v(T_2 - T_1) = e_2 - e_1$$

- If c_p can be taken constant between T_1 and T_2, then, for a quasi-equilibrium constant pressure process

$$q = c_P(T_2 - T_1) = h_2 - h_1$$

Ideal Gas - 1

- **For real gases at low pressure $Pv/T \approx$ constant**
- **We define an ideal gas as a fluid for which**

$$Pv/T = R = \text{constant}$$

- **Therefore real gases at low pressures approximate to ideal gases. *R* has a different value for different gases and is called the specific ideal-gas constant**
- **Ideal gas - (Chemistry) a hypothetical gas whose molecules occupy negligible space and have no interactions, and which consequently obeys the gas law exactly.**

Ideal Gas - 2

- **Summary**

$Pv/T = R$ (constant) $\qquad P_1v_1/T_1 = P_2v_2/T_2$

$e = e(T) \qquad h = h(T)$

$$c_v = \frac{\mathrm{d}e}{\mathrm{d}T} \qquad c_P = \frac{\mathrm{d}h}{\mathrm{d}T} \qquad c_P - c_v = R$$

$$e_2 - e_1 = \int_1^2 c_v \mathrm{d}T \qquad h_2 - h_1 = \int_1^2 c_P \mathrm{d}T$$

$$s_2 - s_1 = \int_1^2 \frac{\mathrm{d}e}{T} + R\ln\left(\frac{v_2}{v_1}\right) = \int_1^2 \frac{\mathrm{d}h}{T} - R\ln\left(\frac{P_2}{P_1}\right)$$

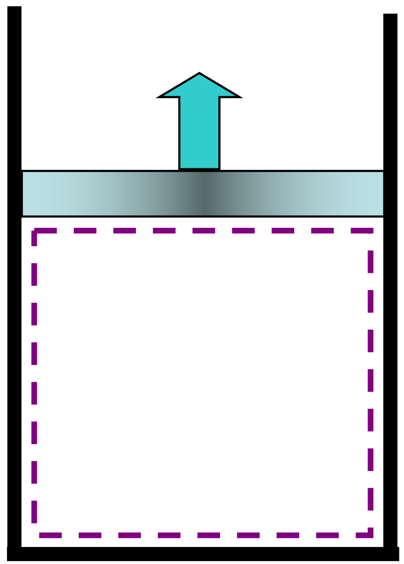
Perfect Gas

- Summary
- $Pv = RT$ and c_v, c_P constant
- $e_2 - e_1 = c_v(T_2 - T_1)$
- $h_2 - h_1 = c_P(T_2 - T_1)$
- $s_2 - s_1$ = 3 expressions in terms of (T, v), (T, P), (P, v)
- For isentropic (constant s) process
- Pv^γ = constant; $P_1 v_1^\gamma = P_2 v_2^\gamma$
- $\gamma = c_P/c_v$ = constant for perfect gas

Fundamental concepts - 13

- **Quasi-equilibrium (quasi static, non-dissipative, internally reversible) process**

Ideal process performed so slowly that system is always in an equilibrium state i.e. during the process the system passes through a continuous sequence of equilibrium states, e.g. compression of a gas in a cylinder *infinitely slowly*.



Fundamental concepts - 14

- <u>Summary</u>

$$E_2 - E_1 = Q + W$$ always true

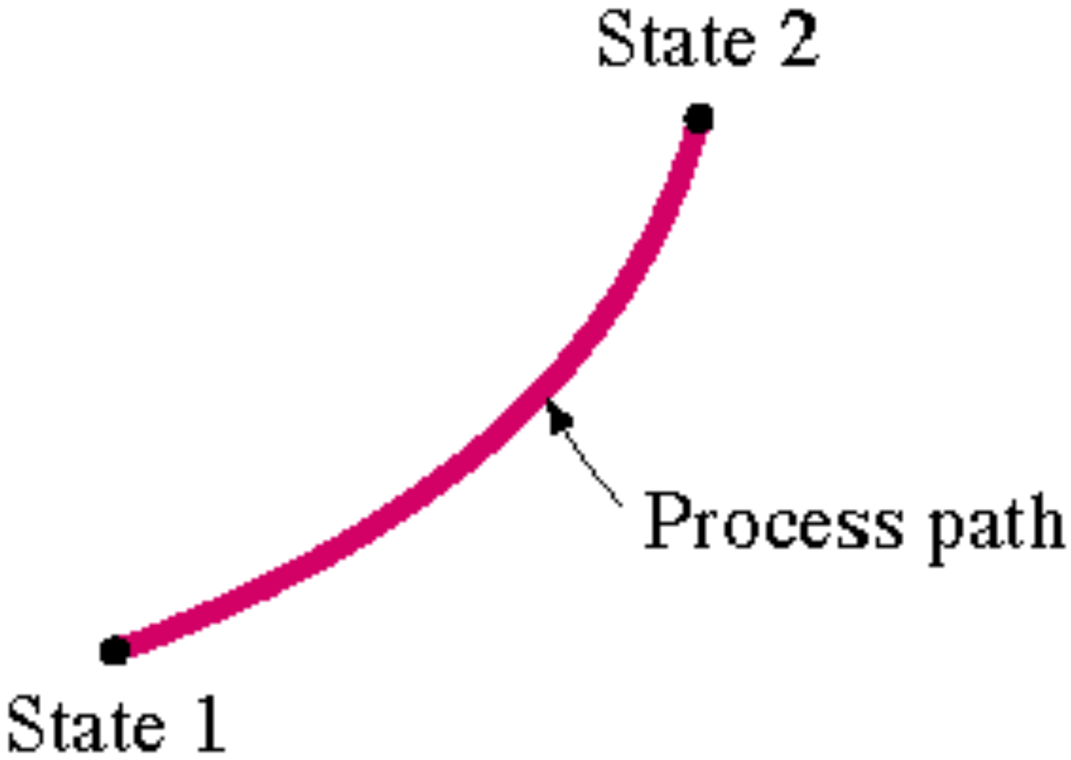
$$W = -\int_{V_1}^{V_2} P\mathrm{d}V$$ finite quasi-equilibrium process

$$Q = \int_{S_1}^{S_2} T\mathrm{d}S$$ finite quasi-equilibrium process

Fundamental Concepts - 15

- **Process**

  Change from one equilibrium state to another

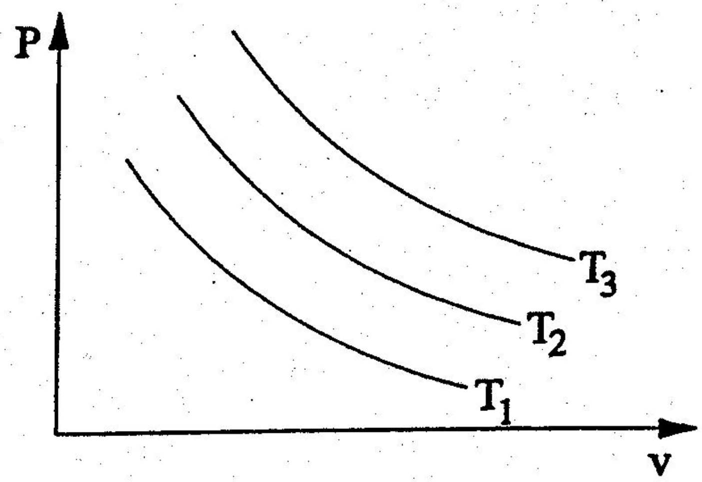


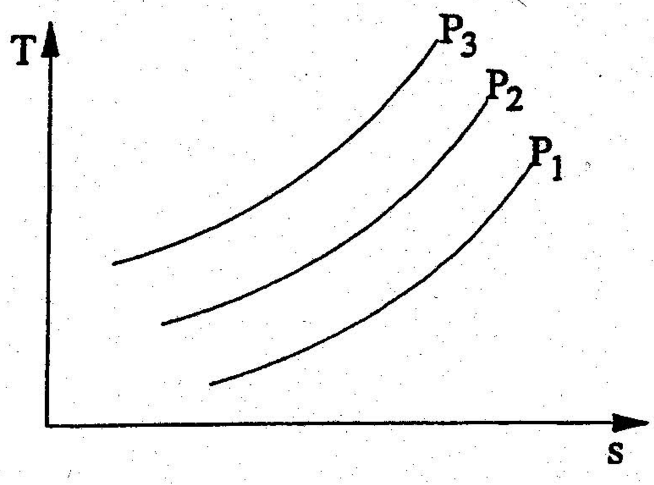
States between 2 end states can be equilibrium or non-equilibrium. ⇨ Work and Heat later.

Fundamental concepts - 16

- **Process illustration**

  ***P* – *V* and *T* – *S* diagrams**





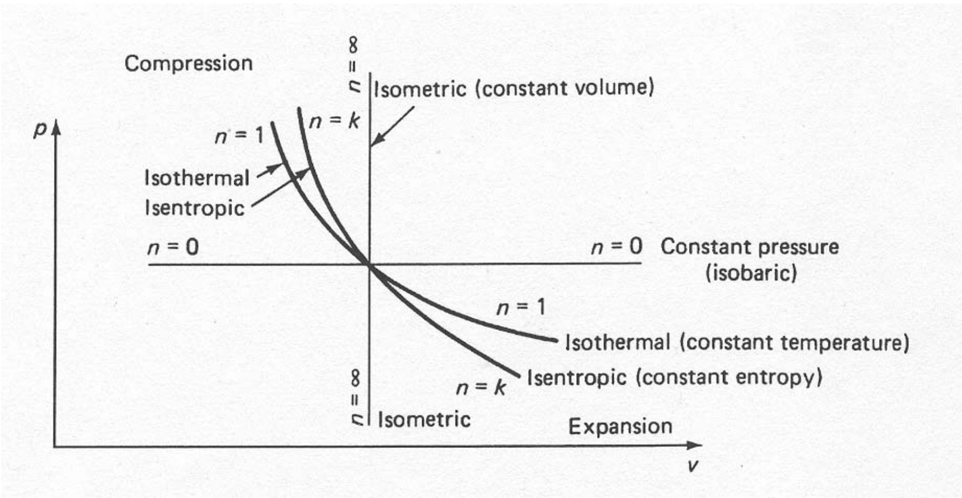
Fundamental Concepts - 17

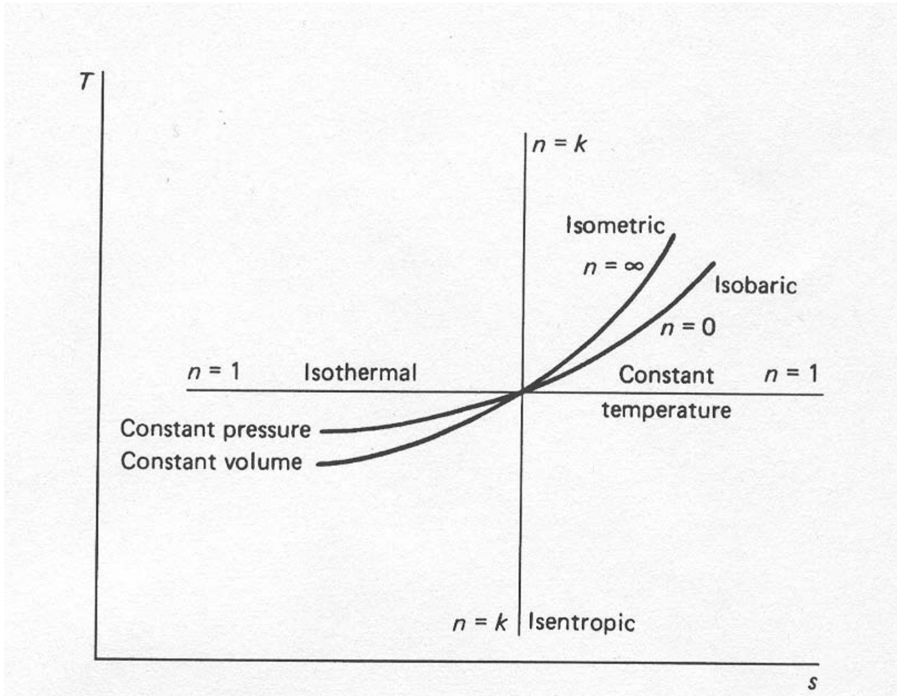
- **Polytropic process**

- Pv^n = constant $\quad -\infty < n < \infty$
-
- Isobaric $\quad P$ = constant $\quad 0$
- Isothermal $\quad T$ = constant $\quad 1$
- Isentropic $\quad S$ = constant $\quad \gamma$
- Isochoric $\quad V$ = constant $\quad -/+\infty$

Fundamental Concepts - 18

- **Polytropic Process**





Fundamental Concepts - 19

- **Polytropic Process**

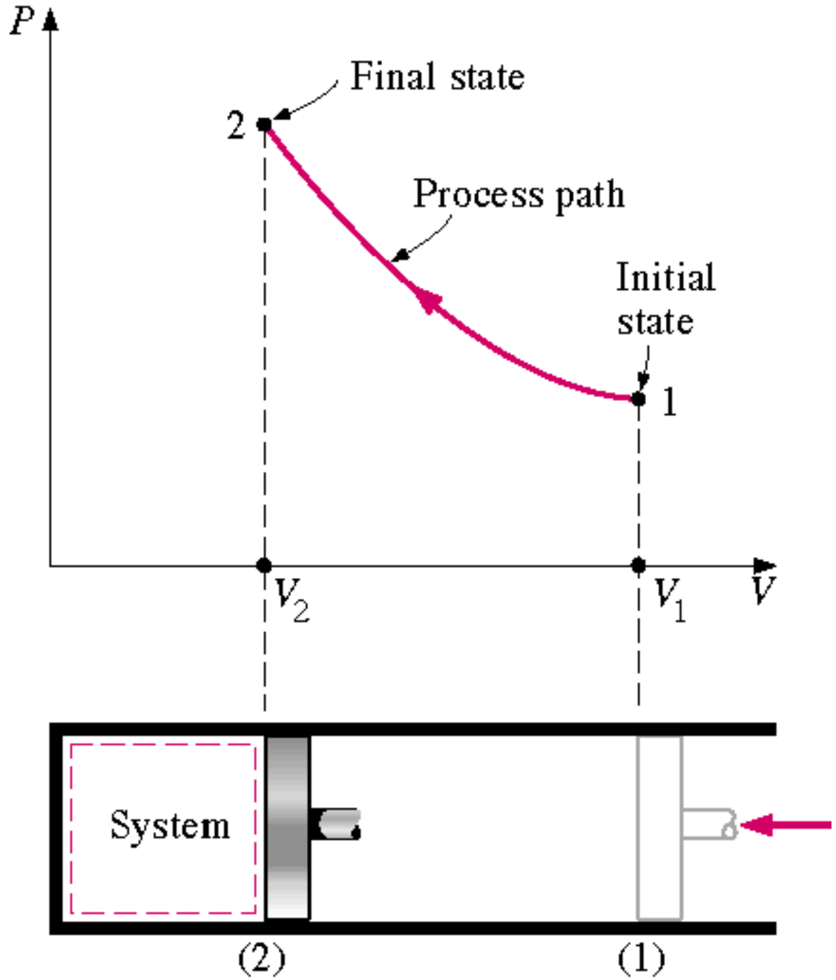
Table 1 Summary of perfect gas relations

Process	Isochoric v=constant	Isobaric P=constant	Isothermal T = constant Pv=constant	Isentropic s = constant $Pv^{\gamma}=\text{const.}$ $Tv^{\gamma-1}=\text{constant}$ $TP^{-\frac{\gamma-1}{\gamma}}=\text{constant}$	Polytropic Pv^{n}=constant $Tv^{n-1}=\text{constant}$ $TP^{-\frac{n-1}{n}}=\text{constant}$
n	∞	0	1	γ	$-\infty$ to $+\infty$
c	c_V	c_p	∞	0	$c_n=c_v\left(\frac{\gamma-n}{1-n}\right)$
P, v, T relation	$\frac{T_1}{T_2}=\frac{P_1}{P_2}$	$\frac{T_1}{T_2}=\frac{v_1}{v_2}$	$P_1v_1=P_2v_2$	$\frac{P_2}{P_1}=\left(\frac{v_1}{v_2}\right)^{\gamma}$ $\frac{T_2}{T_1}=\left(\frac{v_1}{v_2}\right)^{\gamma-1}$ $\frac{T_2}{T_1}=\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$	$\frac{P_2}{P_1}=\left(\frac{v_1}{v_2}\right)^{n}$ $\frac{T_2}{T_1}=\left(\frac{v_1}{v_2}\right)^{n-1}$ $\frac{T_2}{T_1}=\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$
u_2-u_1	$c_v(T_2-T_1)$	$c_v(T_2-T_1)$	0	$c_v(T_2-T_1)$	$c_v(T_2-T_1)$
h_2-h_1	$c_p(T_2-T_1)$	$c_p(T_2-T_1)$	0	$c_p(T_2-T_1)$	$c_p(T_2-T_1)$
s_2-s_1	$c_v\ln\frac{T_2}{T_1}$	$c_p\ln\frac{T_2}{T_1}$	$R\ln\frac{v_2}{v_1}$	0	$c_n\ln\frac{T_2}{T_1}$
w	0	$P(v_2-v_1)$	$P_1v_1\ln\frac{v_2}{v_1}$	$\frac{P_2v_2-P_1v_1}{1-k}$	$\frac{P_2v_2-P_1v_1}{1-n}$
q	$c_v(T_2-T_1)$	$c_p(T_2-T_1)$	$P_1v_1\ln\frac{v_2}{v_1}$	0	$c_n(T_2-T_1)$

Fundamental concepts - 20

- **Process**

Process illustration (*P – V* diagram)

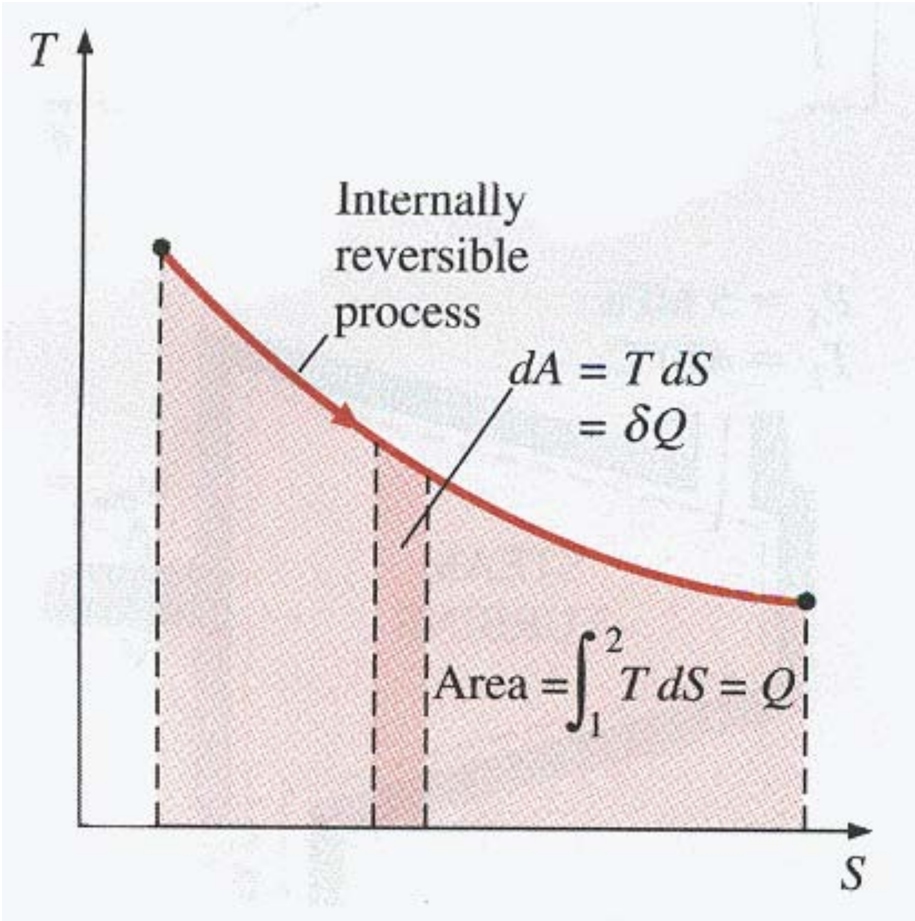


Property?

Fundamental concepts - 21

- **Process**

Process illustration (*T – S* diagram)

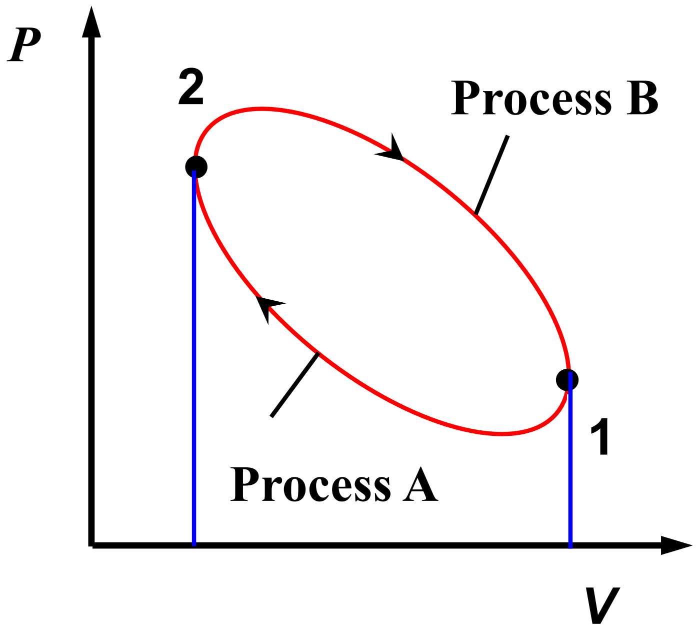


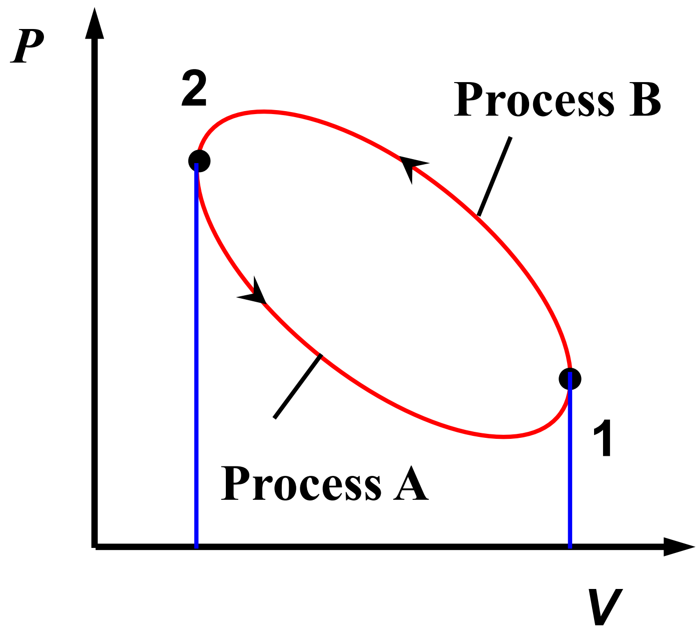
Property?

Fundamental concepts - 22

- **Cycle**

  A serious of a connected processes with identical end states

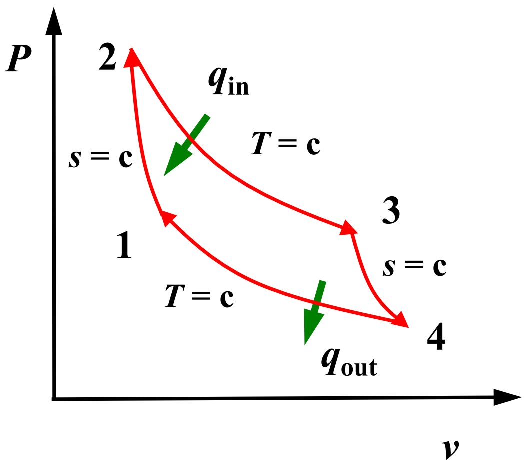


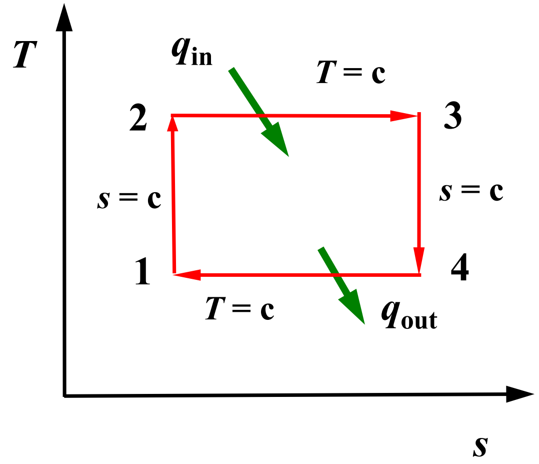


Property?

Fundamental concepts - 23

- **Carnot cycle – an example**





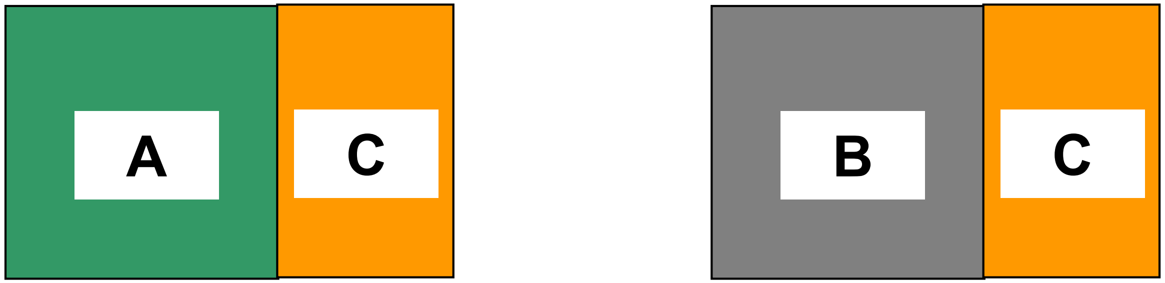
Thermal efficiency = Desired output/Required input

COP **(Coefficient Of Performance) = Desired output/Required input**

Laws of thermodynamics - 1

- **The zeroth law of thermodynamics**

  R. H. Fowler (1931)



Laws of thermodynamics - 2

- **The first law of thermodynamics**

For <u>any</u> process of a stationary system

$$W + Q = E_2 - E_1$$

Steady flow energy equation (SFEE)

$$W + Q = \Sigma[m(h + v^2/2 + gz)]_2 - \Sigma[m(h + v^2/2 + gz)]_1$$

Laws of thermodynamics - 3

- **Entropy and the 2nd Law of thermodynamics**

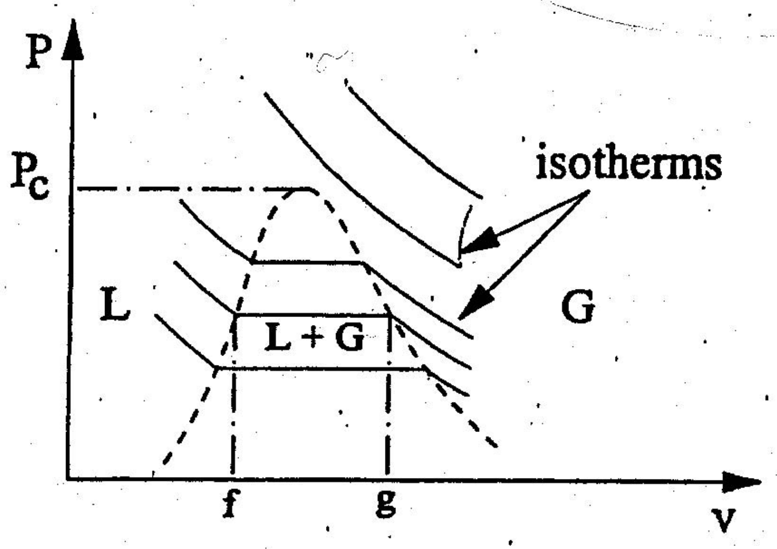
Spontaneous (no outside influence) processes lead to increase in entropy. This is the essence of the Second Law of Thermodynamics.

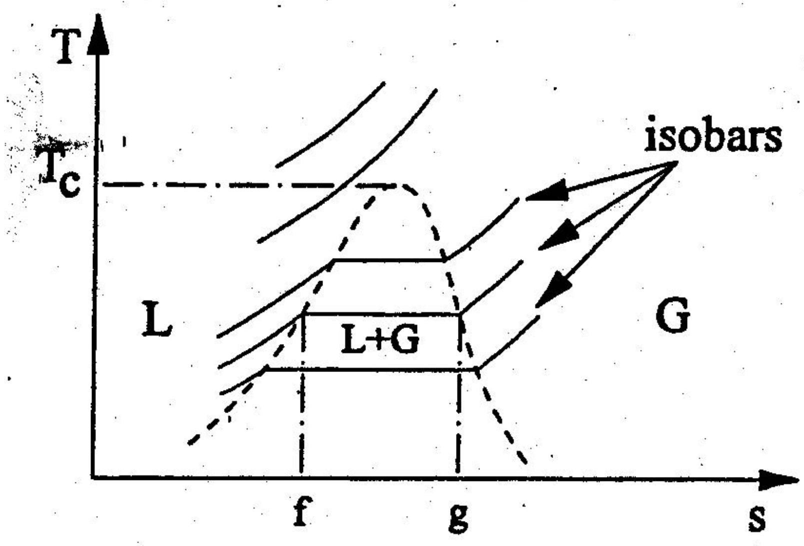
- **dE = 0**
- **dS ≥ 0**

For an isolated system the internal energy is constant and the entropy can only increase. Entropy is constant for ideal reversible process

Property of Pure Substances

- **The *P-V-T* Surface for a Real Substance**





Average specific properties for 2-phase states

"Quality" or "dryness" x is defined

so that $y = \dfrac{m_f y_f + m_g y_g}{m_f + m_g}$

$= (1 - x) y_f + x y_g$

Note: at $x = 0$, $y = y_f$

$x = 1$, $y = y_g$

We also define, for convenience,

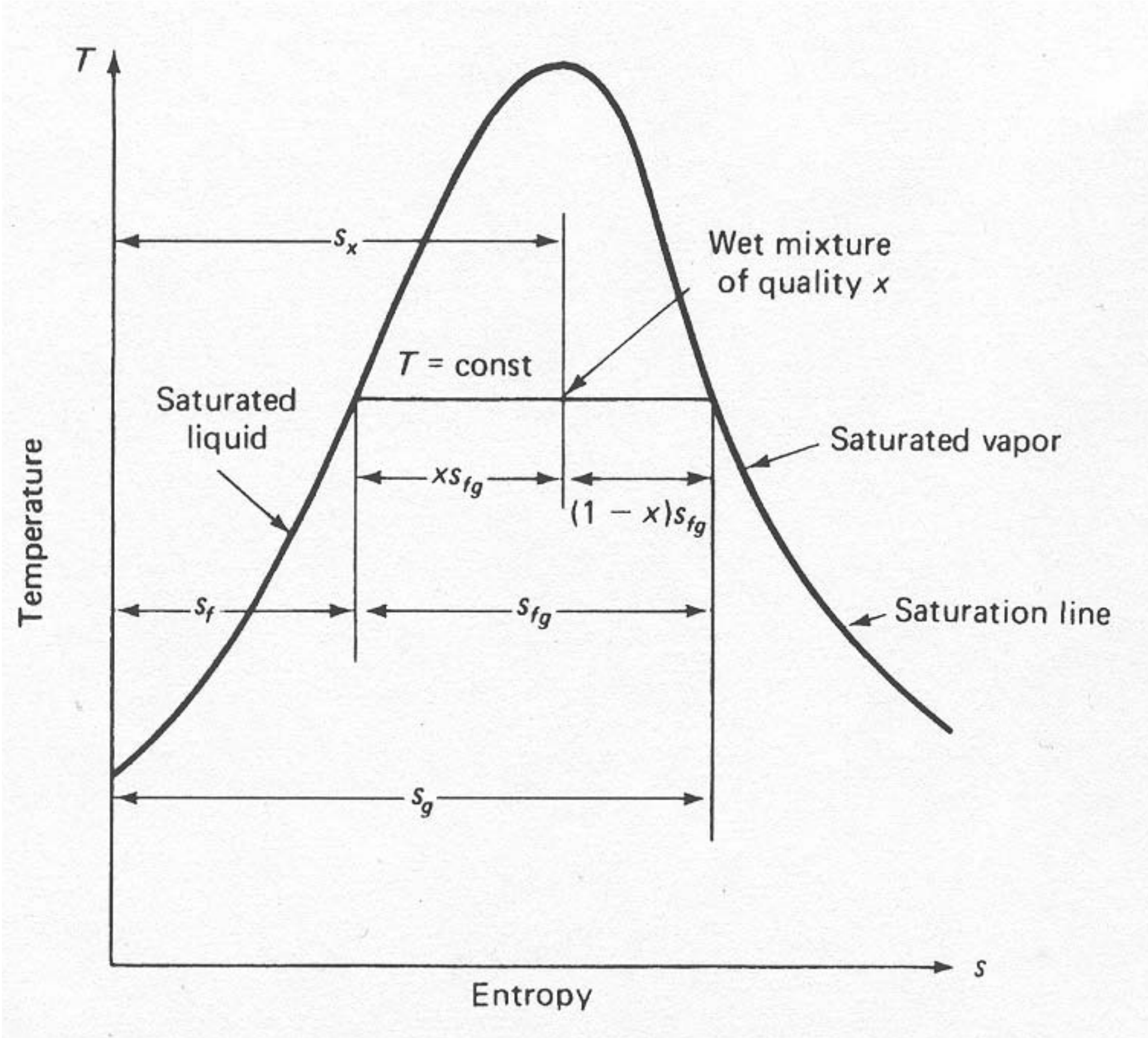
$$y_{fg} = y_g - y_f$$

so that

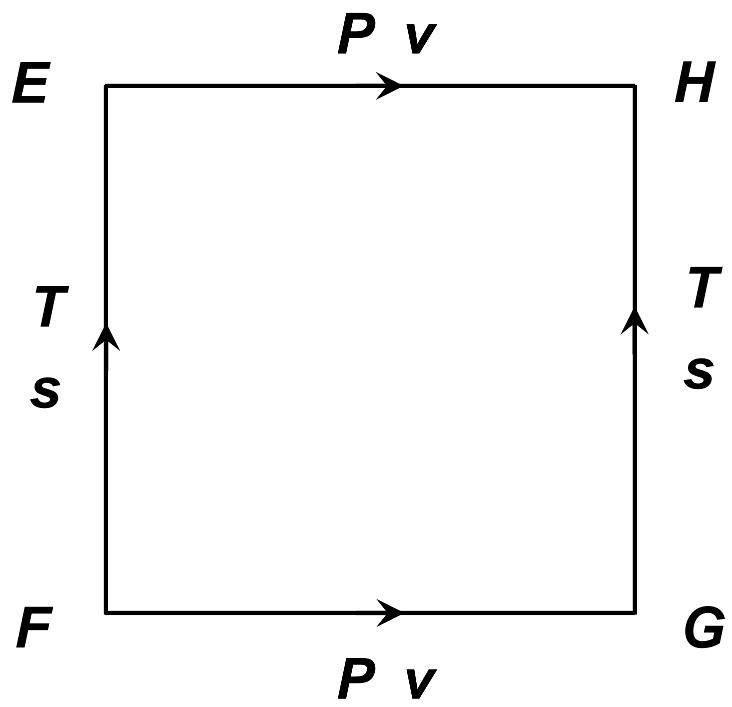
$$y = (1 - x) y_f + x(y_{fg} + y_f)$$

$$= y_f + x y_{fg}$$

Average specific properties for 2-phase states

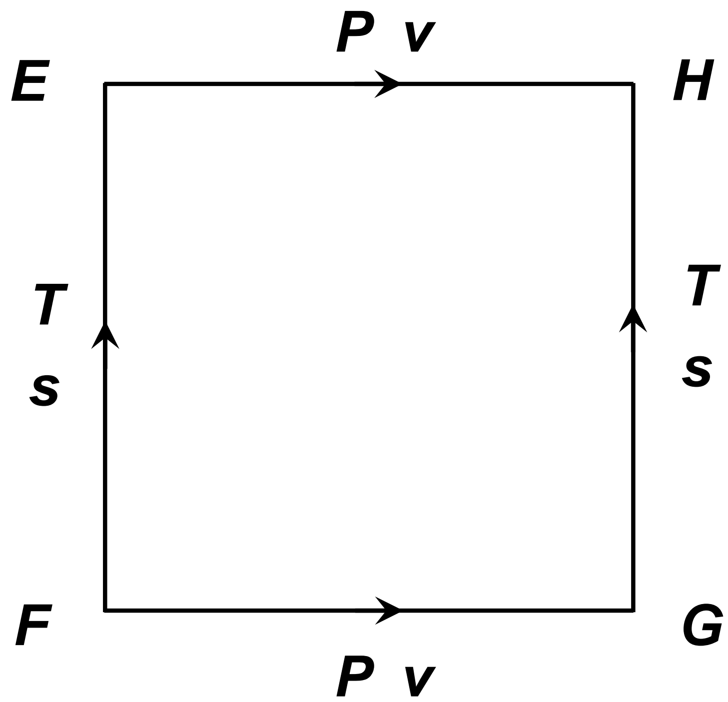


Relation of properties - 1



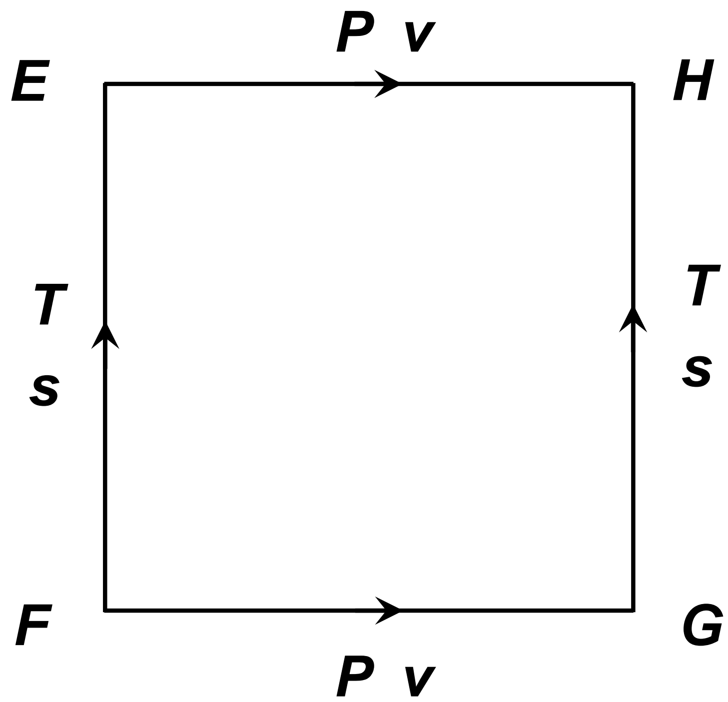
F – Helmholtz function; *G* – Gibbs function; *H* – enthalpy

Relation of properties - 2



$E = F + TS$	$E = H - PV$
$F = E - TS$	$F = G - PV$
$G = F + PV$	$G = H - TS$
$H = E + PV$	$H = G + TS$

Relation of properties - 3



$$\mathrm{d}e = T\mathrm{d}s - P\mathrm{d}v$$
$$\mathrm{d}h = T\mathrm{d}s + v\mathrm{d}P$$
$$\mathrm{d}f = -s\mathrm{d}T - P\mathrm{d}v$$
$$\mathrm{d}g = -s\mathrm{d}T + v\mathrm{d}P$$

$$\mathrm{d}(\mathrm{corner}) = \sum(\mathrm{near})\mathrm{d}(\mathrm{far})$$

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