

# RME1102

## Fundamentals of Mechanical Engineering

### Lecture 2

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# Previous lecture summary

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- Scope of mechanical engineering
- Source of energy
- Basic definition: system, boundary condition, and surrounding
- Properties of boundary
- Different systems: closed, open, adiabatic, and isolated

# Thermodynamic Property

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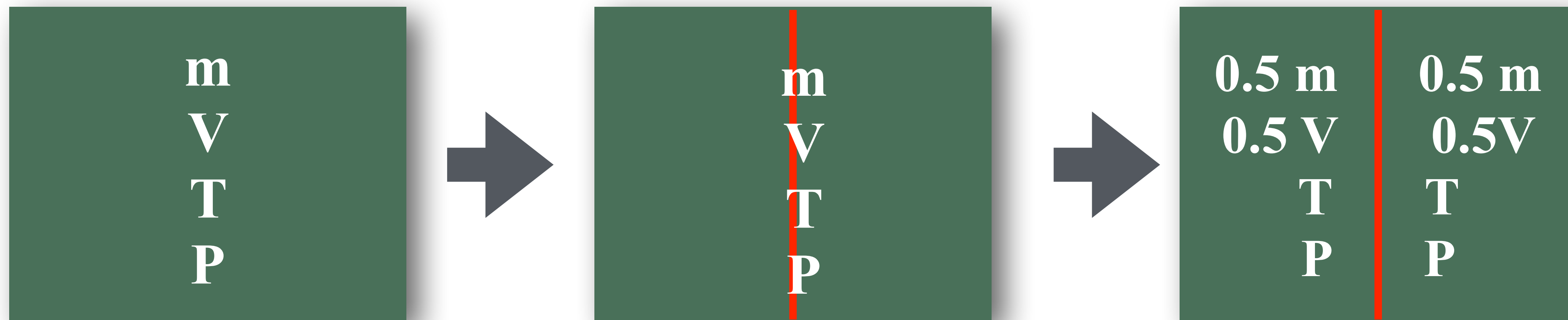
- Any characteristic of a system is called a property.
- A property is a quantity whose numerical value depends on the state but not on the history of the system.  
Example: Pressure (P), Temperature (T), Volume (V), Mass (m), Density ( $\rho$ ), Specific gravity
- Density ( $\rho$ ): mass per unit volume.
- Specific gravity (SG): density of a substance is given relative to the density of a well-known substance.

$$SG = \frac{\rho_s}{\rho_w(\text{ at } 4^\circ\text{C})}$$

- Specific weight: weight of unit volume of a substance.

# Property: classification

- Intensive properties: Do not depend on the size of the system (**independent of system mass**). **Examples include P and T.**
- Extensive Properties: Do depend on the size or extent of the system. **Examples include m, V and U.**



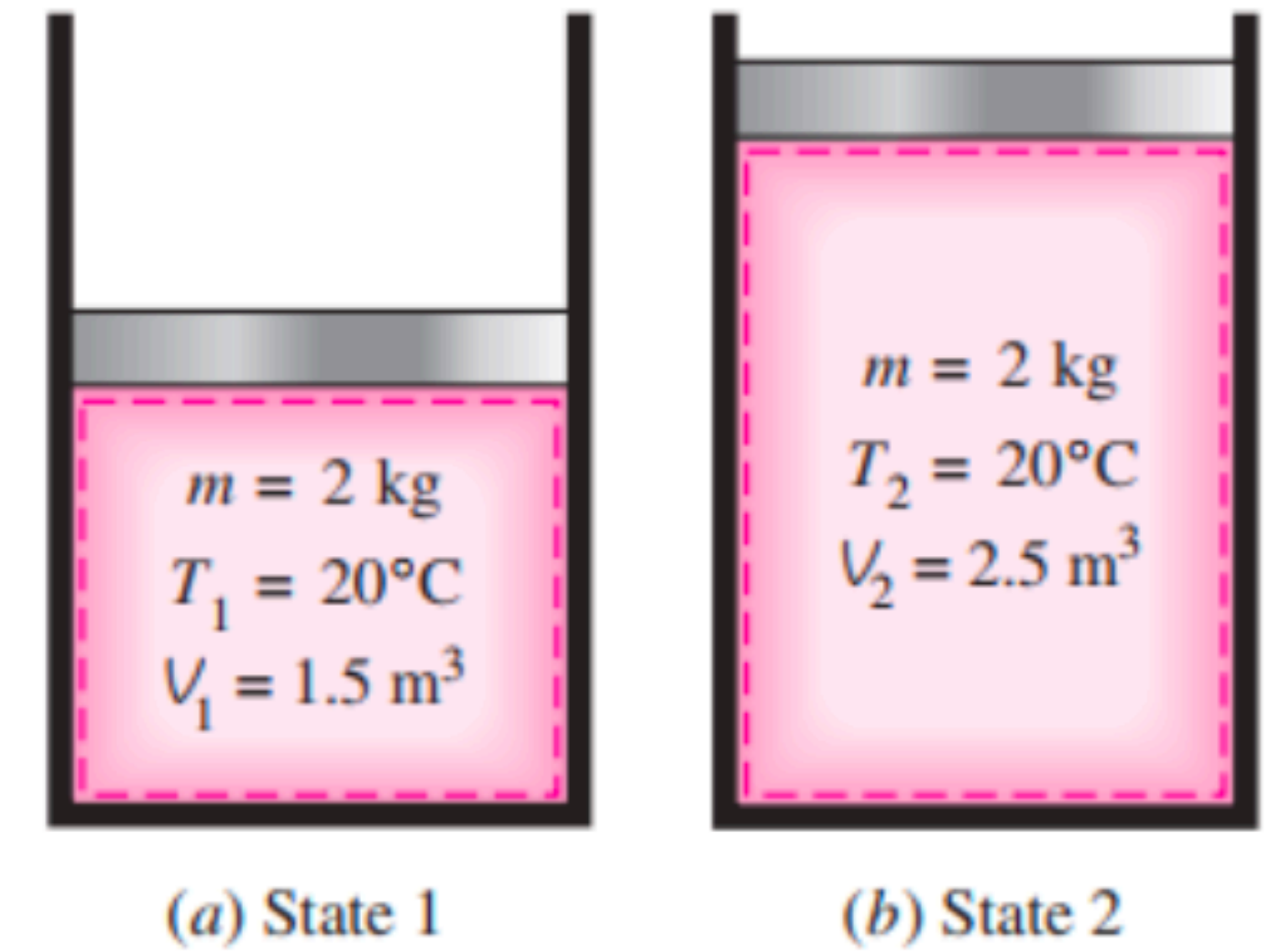
# Property: classification, cont'd

- Specific properties: extensive properties per unit mass.

Property	Extensive	Intensive
Mass	$m$	$\rho$
Volume	$\tilde{V}$	$v$
KE	$\frac{1}{2}mV^2$	$\frac{1}{2}V^2$
PE	$mgZ$	$gZ$
Total Energy	$E$	$e$
Internal Energy	$U$	$u$
Enthalpy	$H$	$h$
Entropy	$S$	$s$

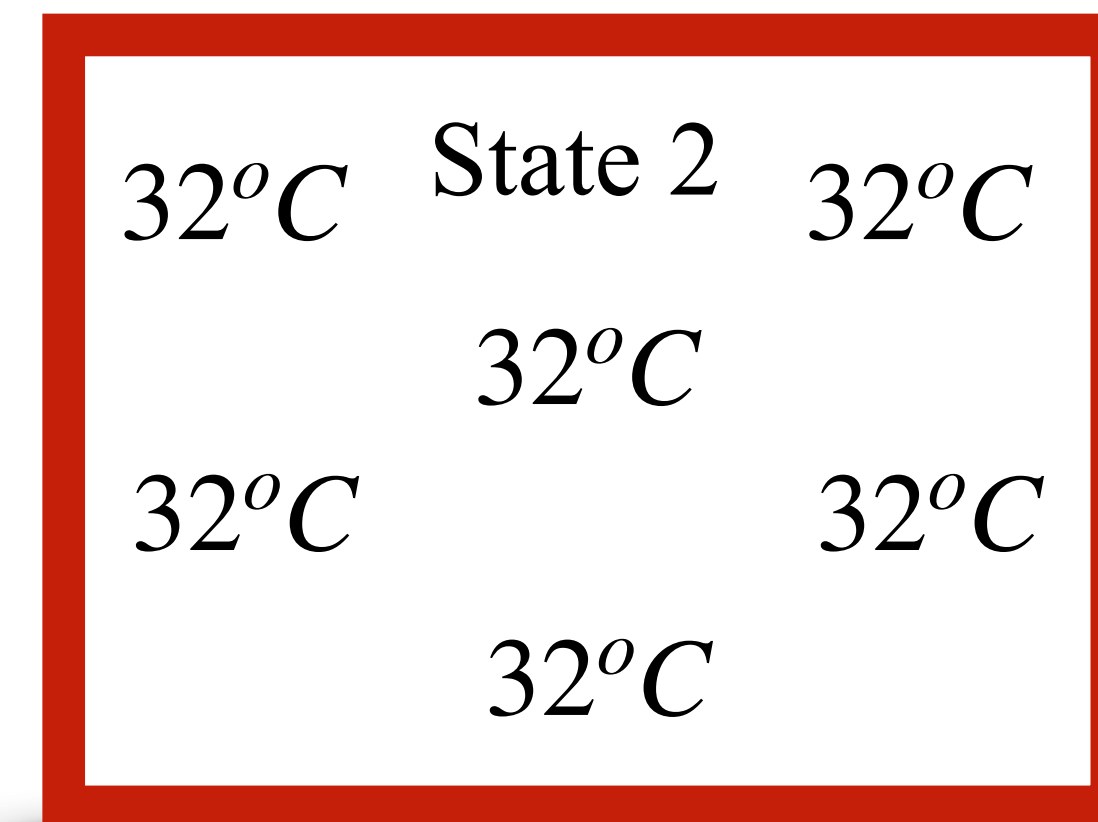
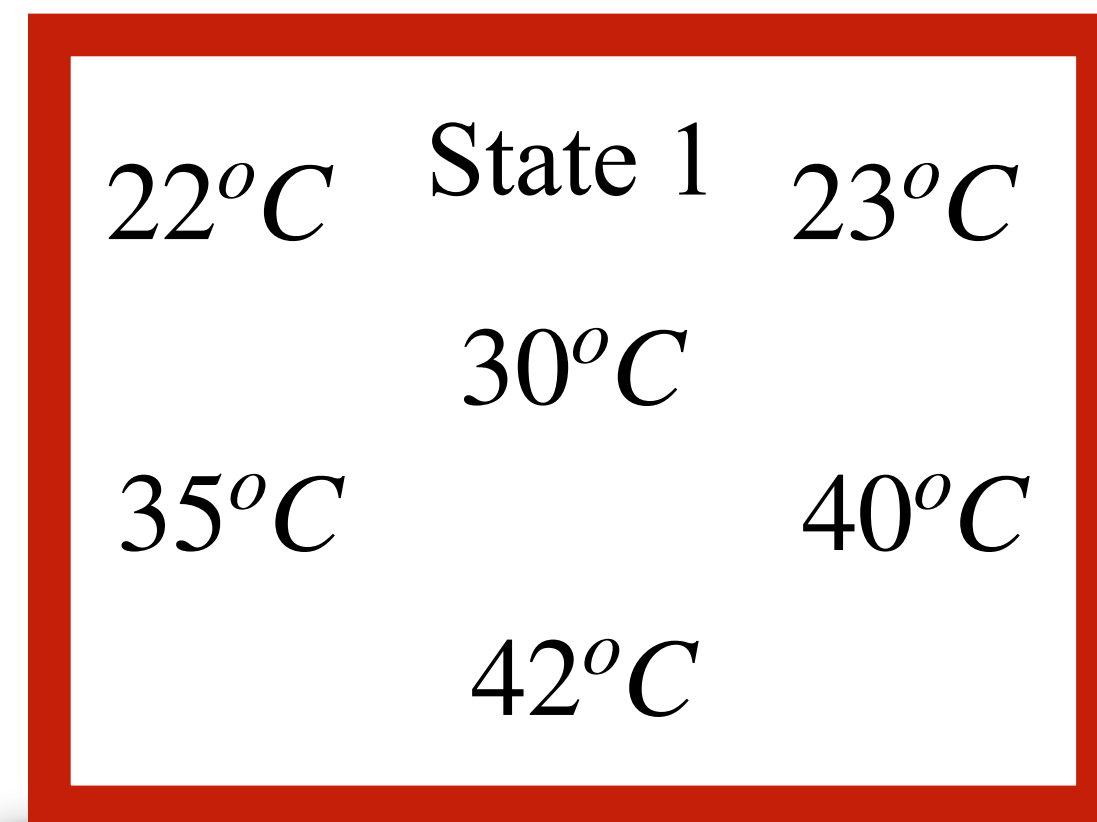
# State and Equilibrium

- **State:** The condition of a system at any instance of time is determined by its intensive properties. Specifying a certain number of properties is sufficient to fix a state. If the value of even one property changes, the state will change to a different one.
- **Equilibrium:** The word equilibrium implies a state of balance.
- The thermodynamic properties are defined at equilibrium states.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system
- **Quasi-equilibrium:** A process during which the system only deviates from equilibrium by **an infinitesimal amount**. A quasi-equilibrium process can be viewed as a sufficiently slow process that allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts.



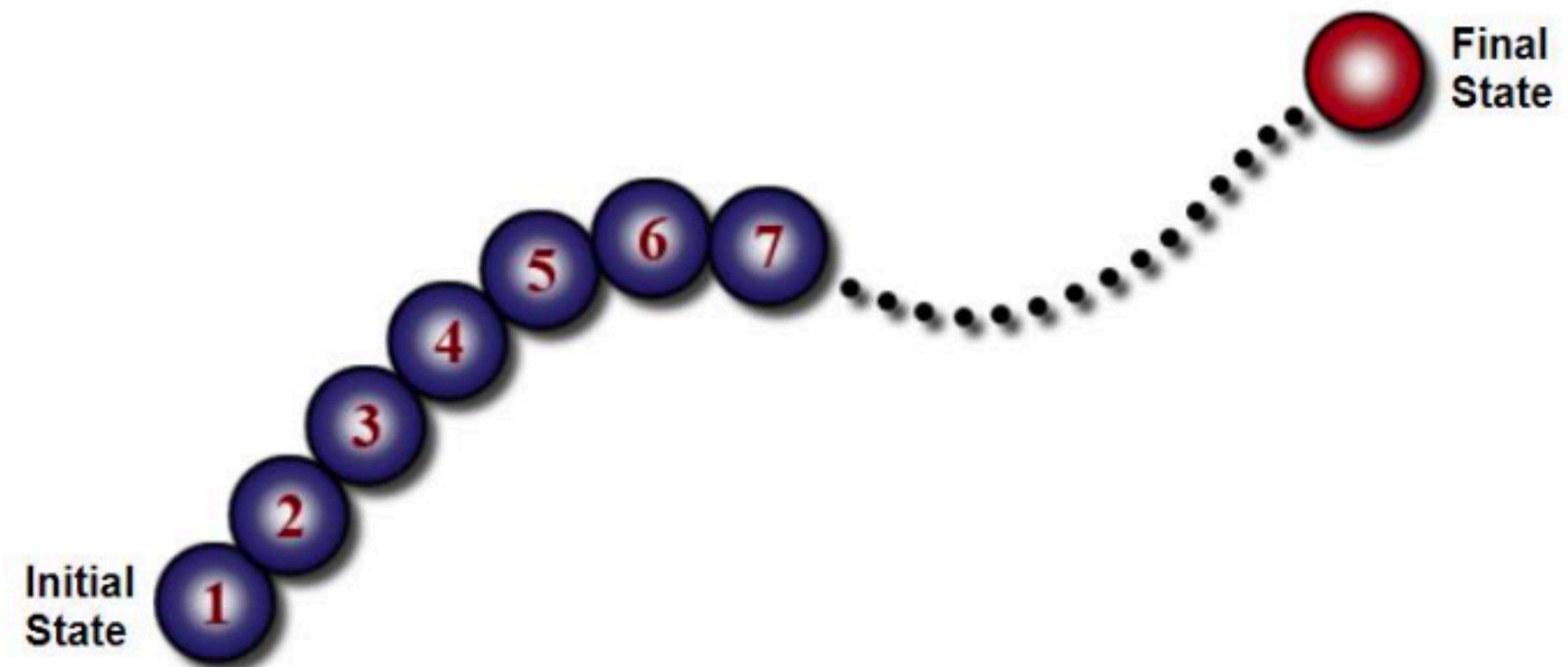
# Condition for thermodynamic equilibrium

- A system in thermodynamic equilibrium satisfies the following stringent requirements:
  - **Mechanical Equilibrium:** no unbalance forces acting on any part of the system or the system as a whole.
  - **Thermal Equilibrium:** no temperature differences between parts of the system or between the system and the surrounding.
  - **Chemical Equilibrium:** no chemical reactions within the system and no motion of any chemical species from one part to another part of the system.



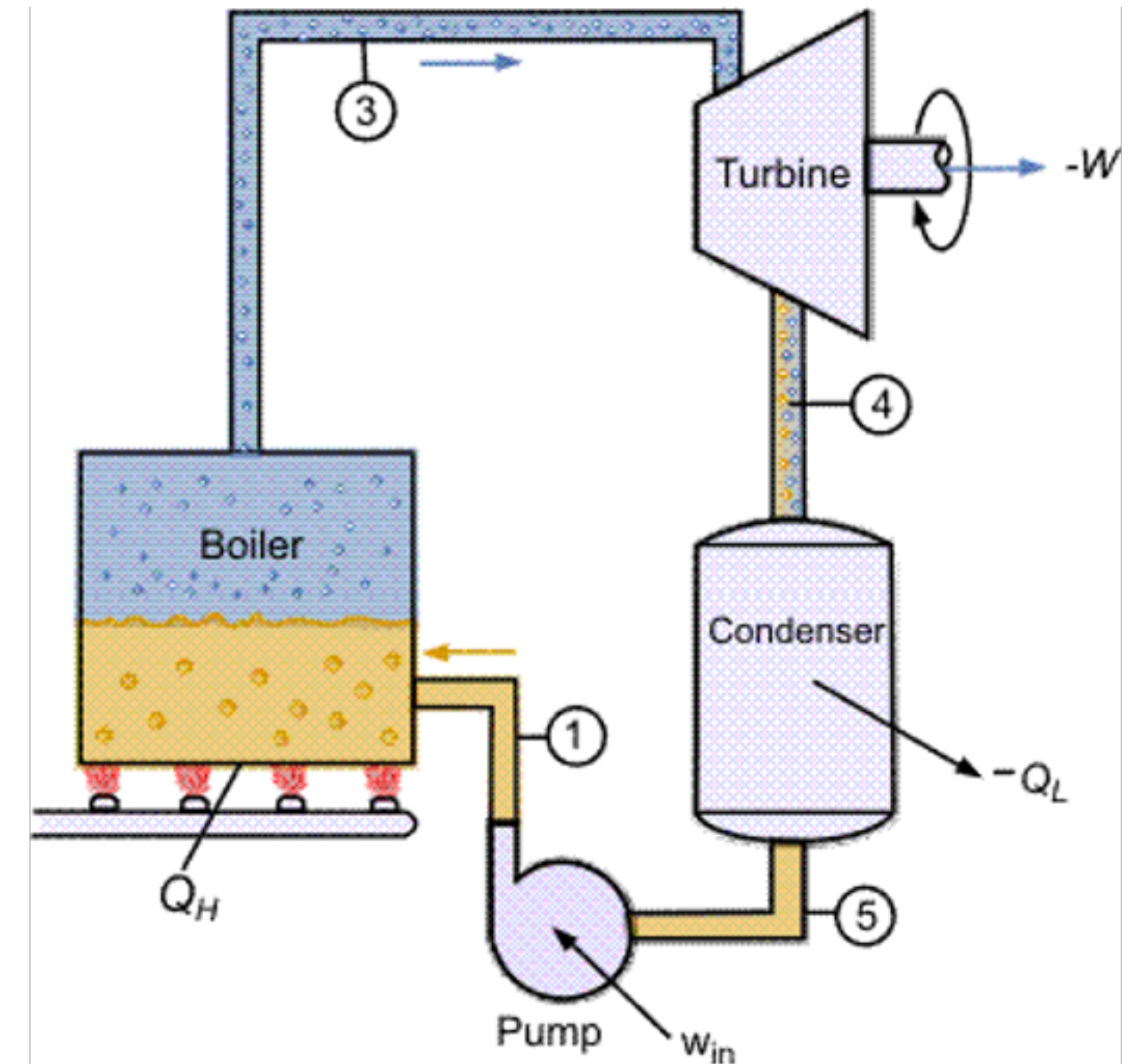
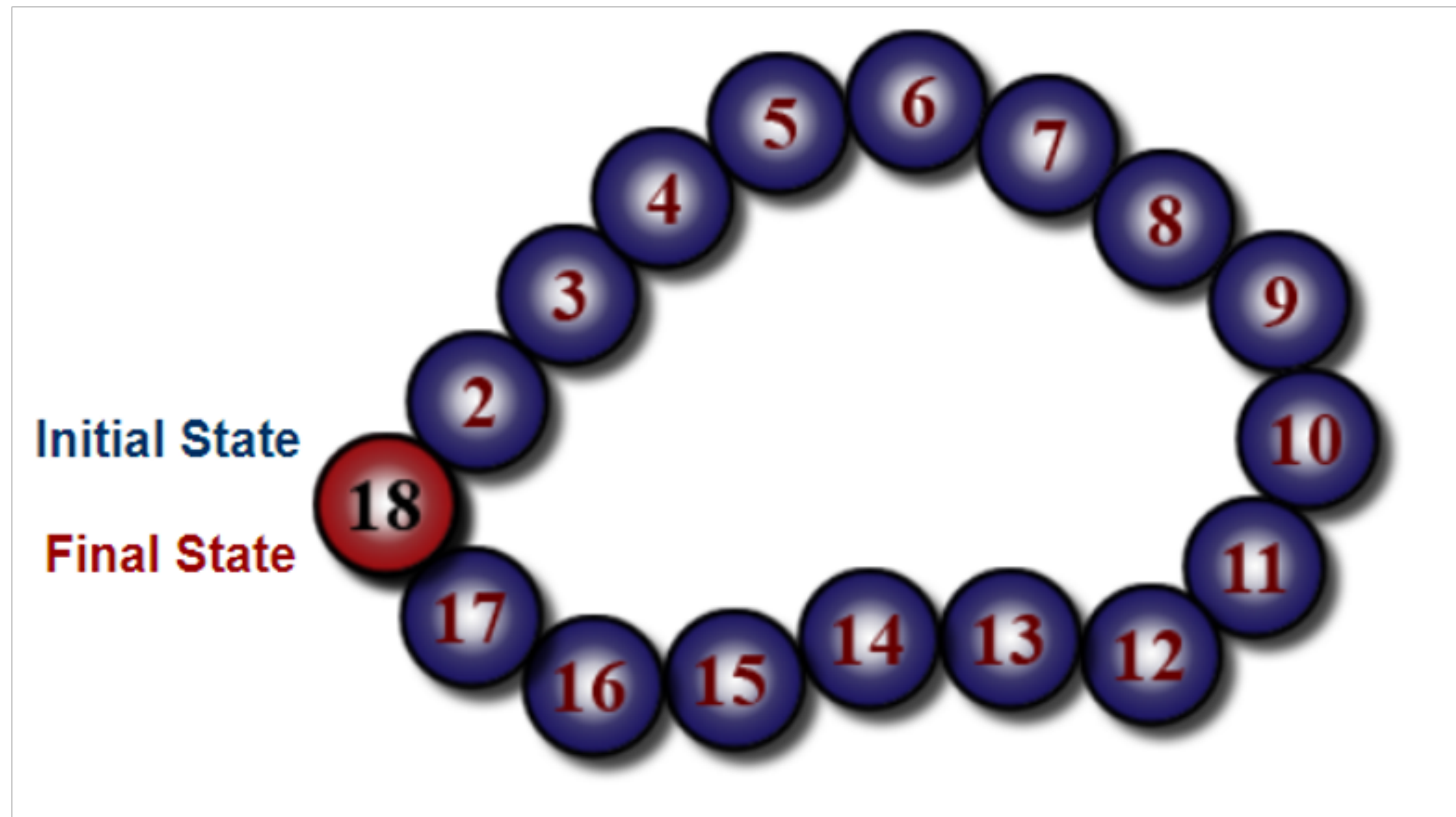
# Thermodynamic process

- A thermodynamic process is the succession of thermodynamic states that a system passes through as it goes from an initial state to a final state
- Some Common Process:
  - Isothermal : constant **Temperature**.
  - Isentropic: constant **Entropy**.
  - Isoenthalpic: constant **Enthalpy**.
  - Isobaric: constant **Pressure**.
  - Isochoric: constant **Volume**.



# Thermodynamic cycle

- A cycle is a very special type of process in which the initial and final states are the same



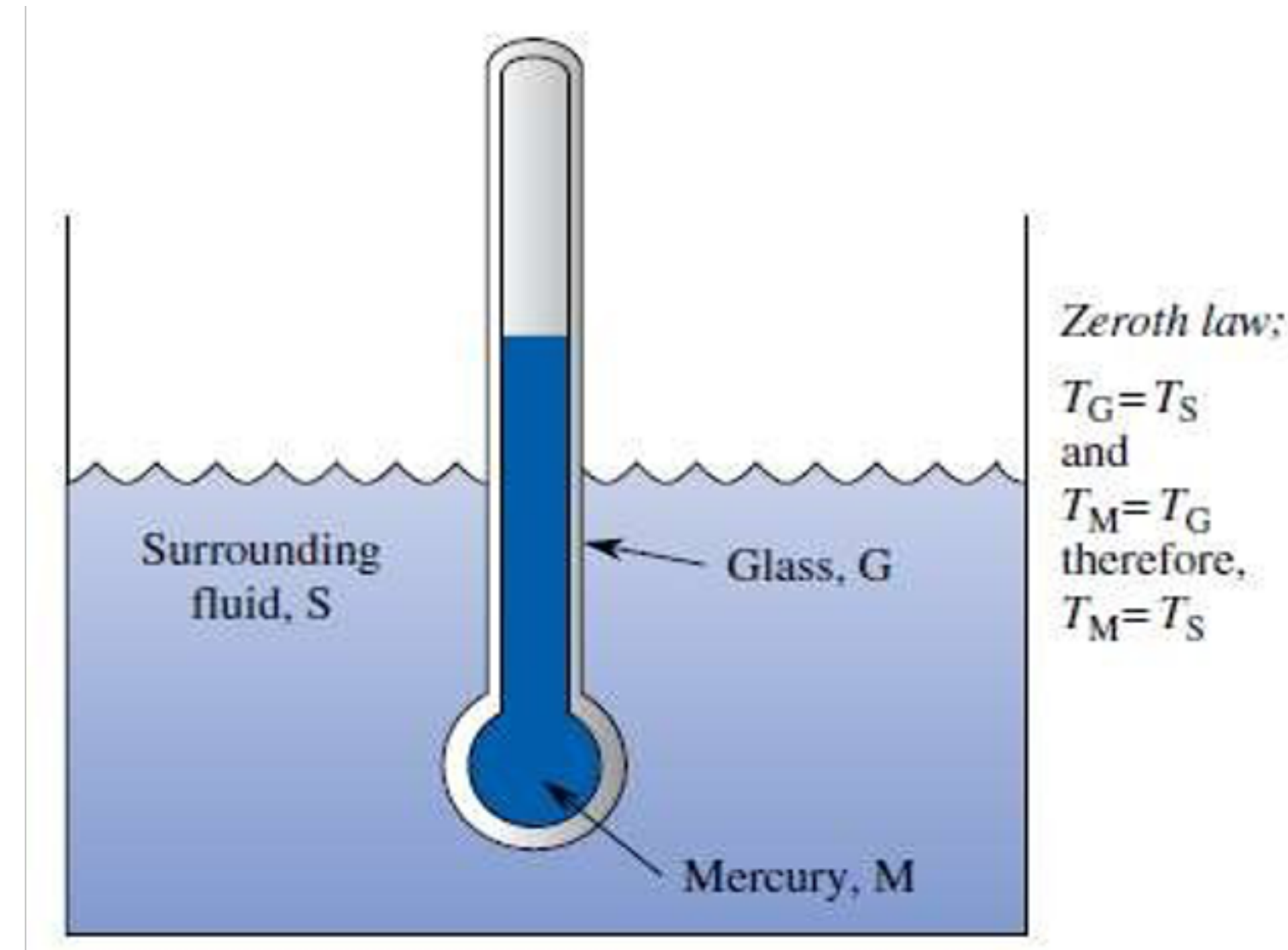
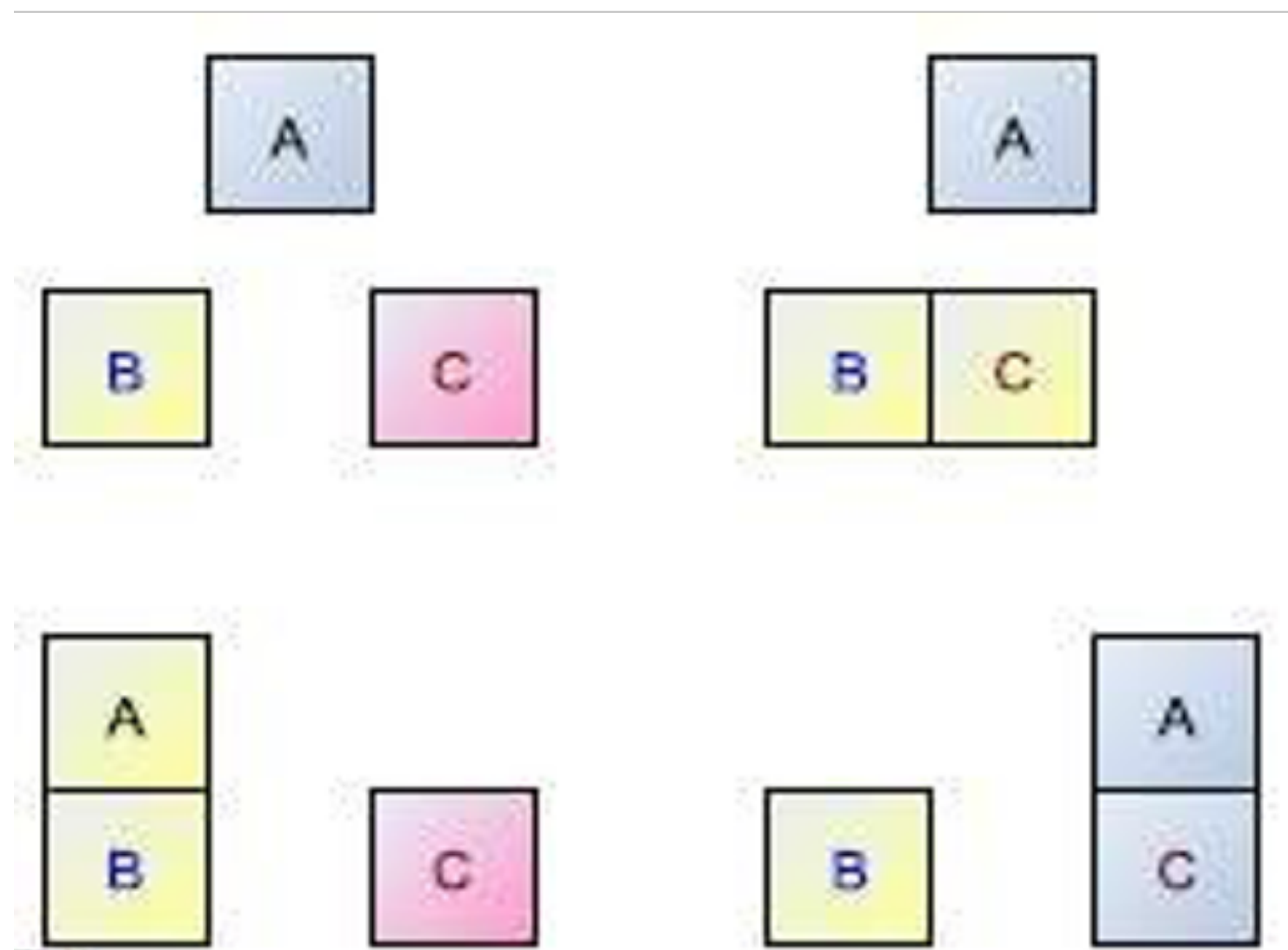
# Zeroth Law of thermodynamics

Consider three thermodynamic systems, A, B, and C.

If system A is in thermal equilibrium with system C

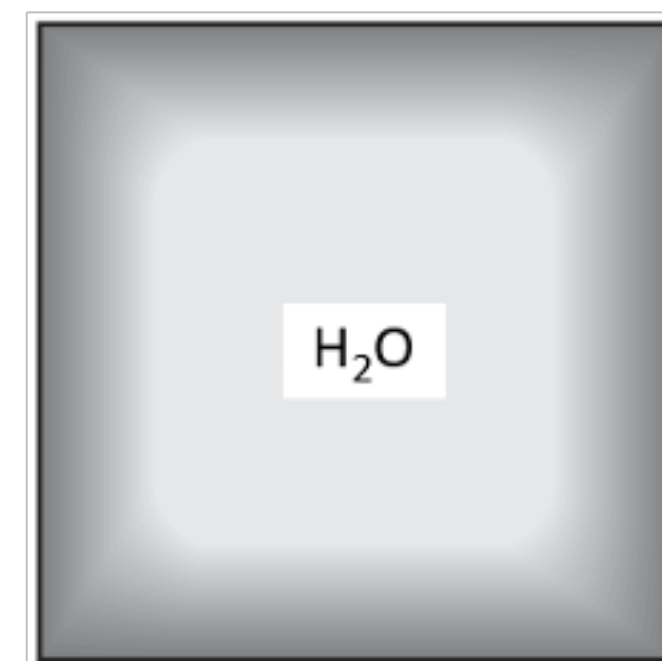
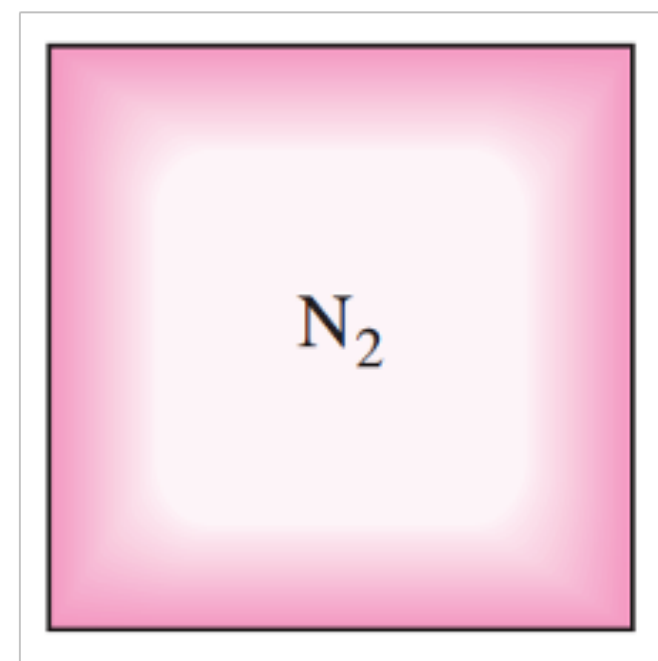
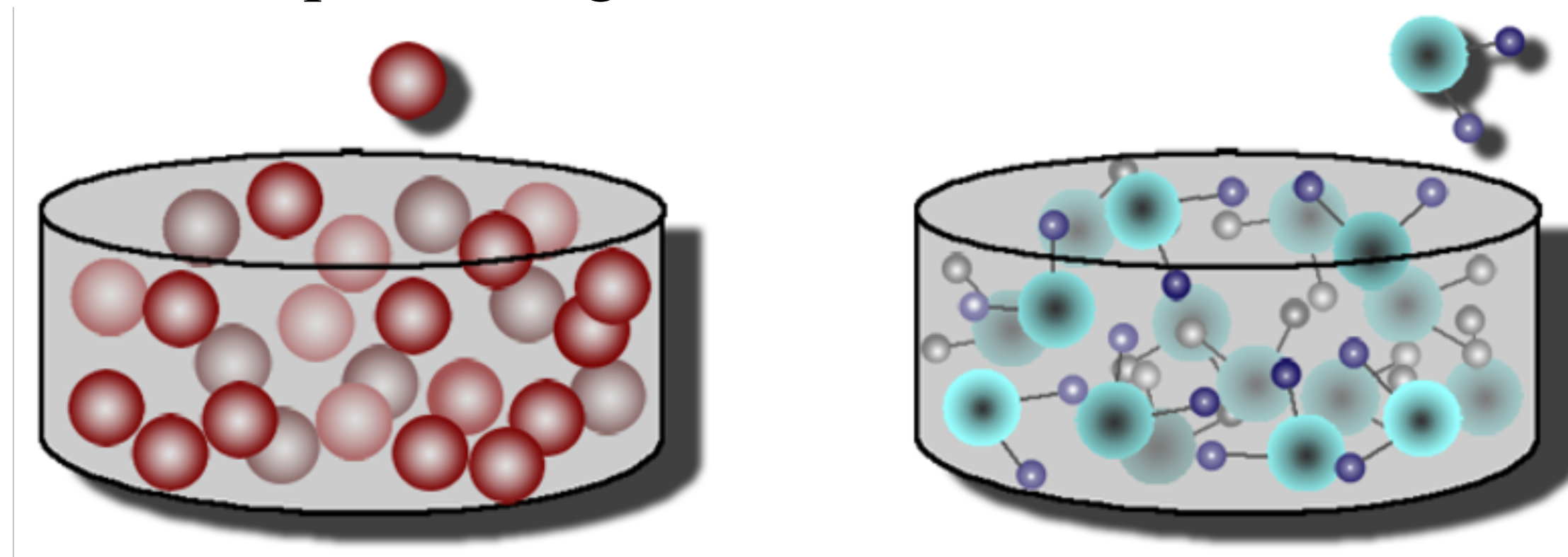
& system B is in thermal equilibrium with system C,

**Then system A is in thermal equilibrium with system B**

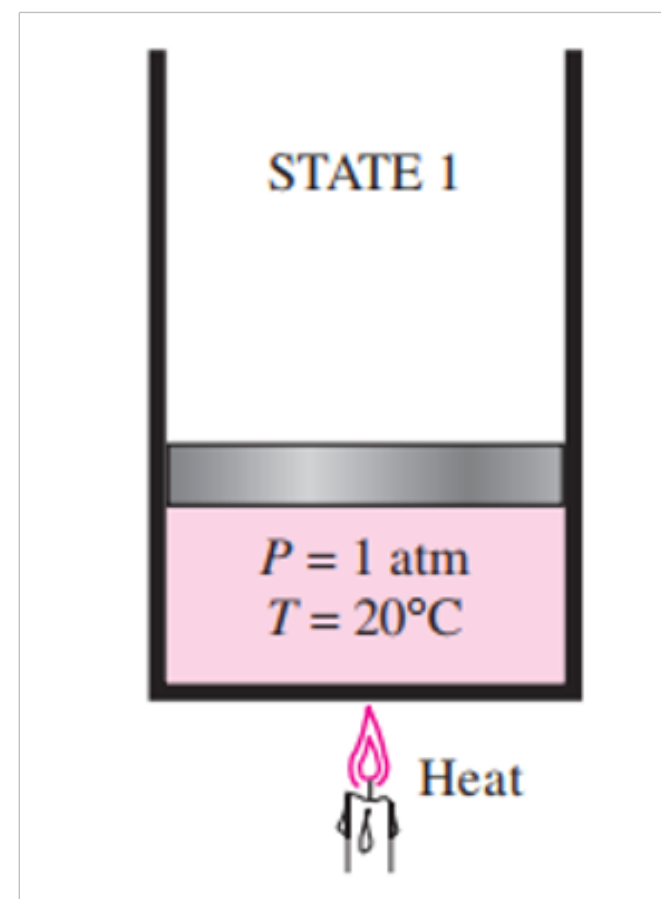


# Pure substance and its phase

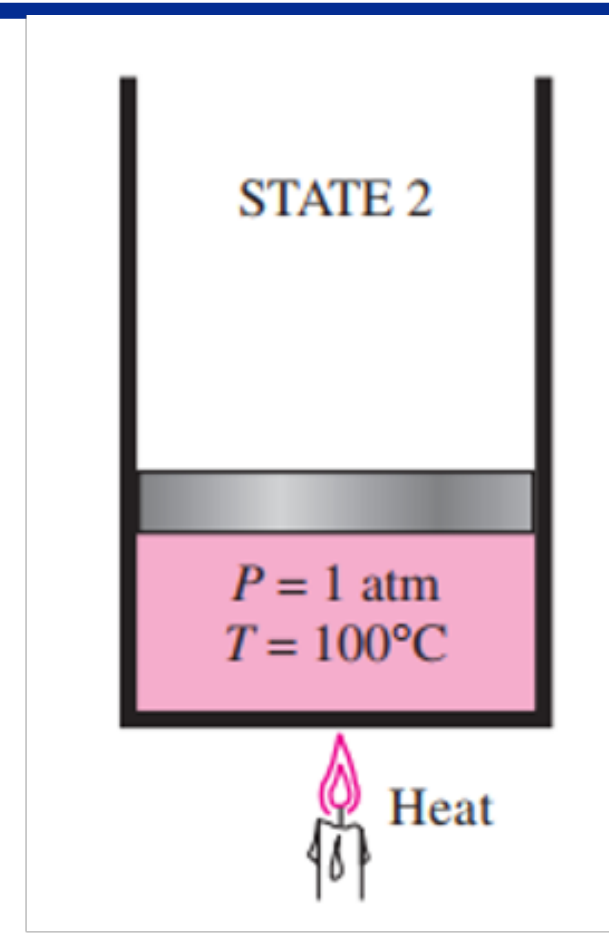
- A pure substance is one that has a homogeneous and invariable chemical composition.
- It may exist in more than one phase, but the chemical composition is the same in all phases.
- Three principal phases—solid, liquid, and gas.



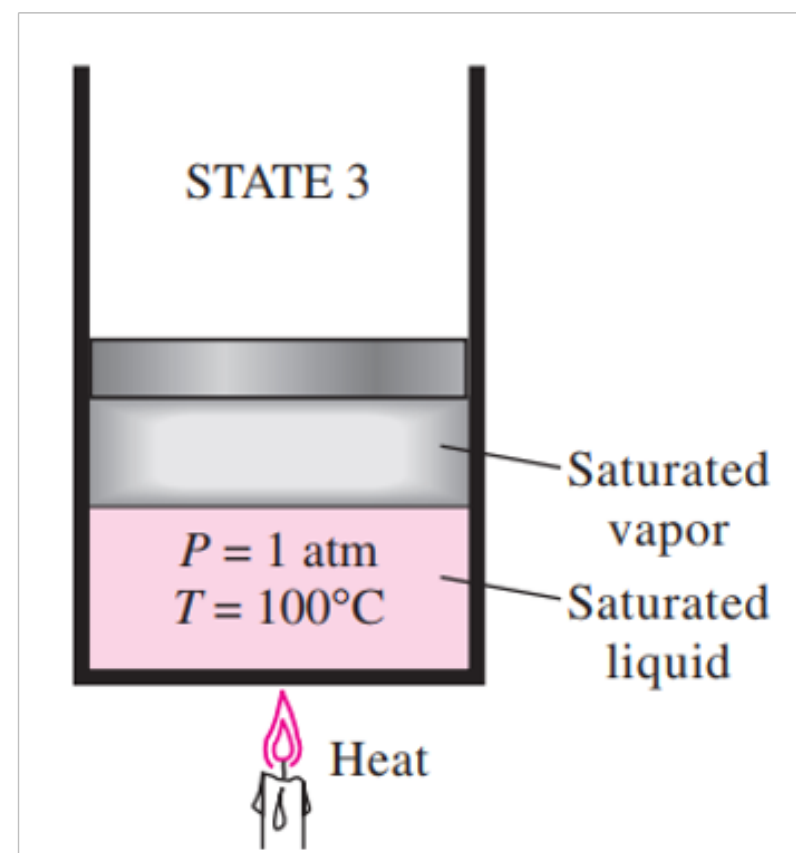
# Phase change: pure substance (water)



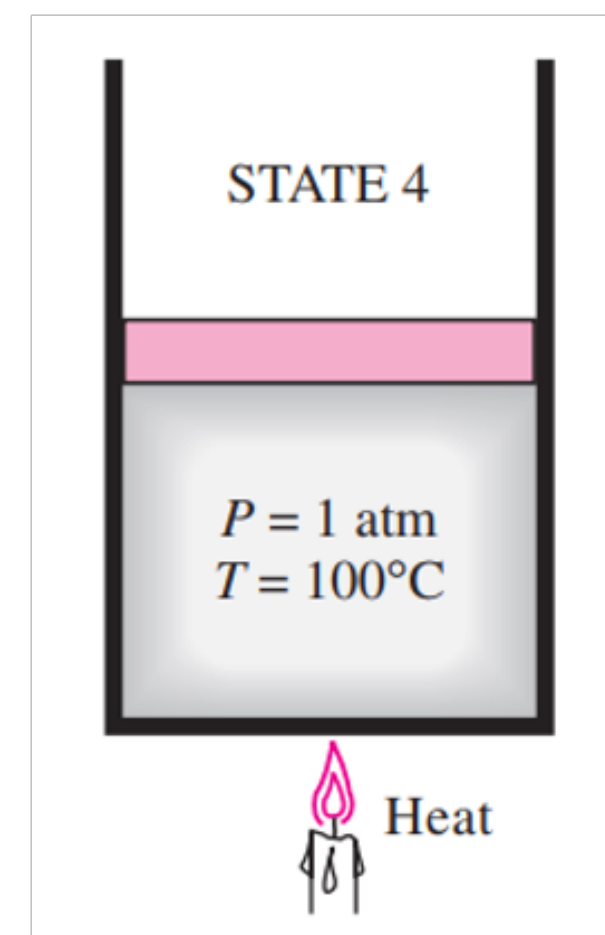
*Compressed/ Sub-cooled liquid*



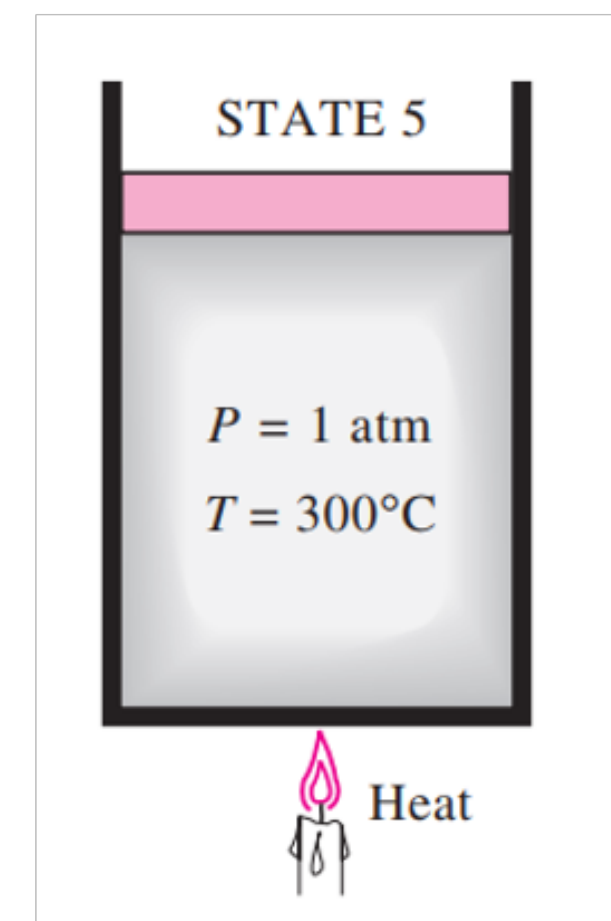
*Saturated Liquid  
 (about to vaporize)*



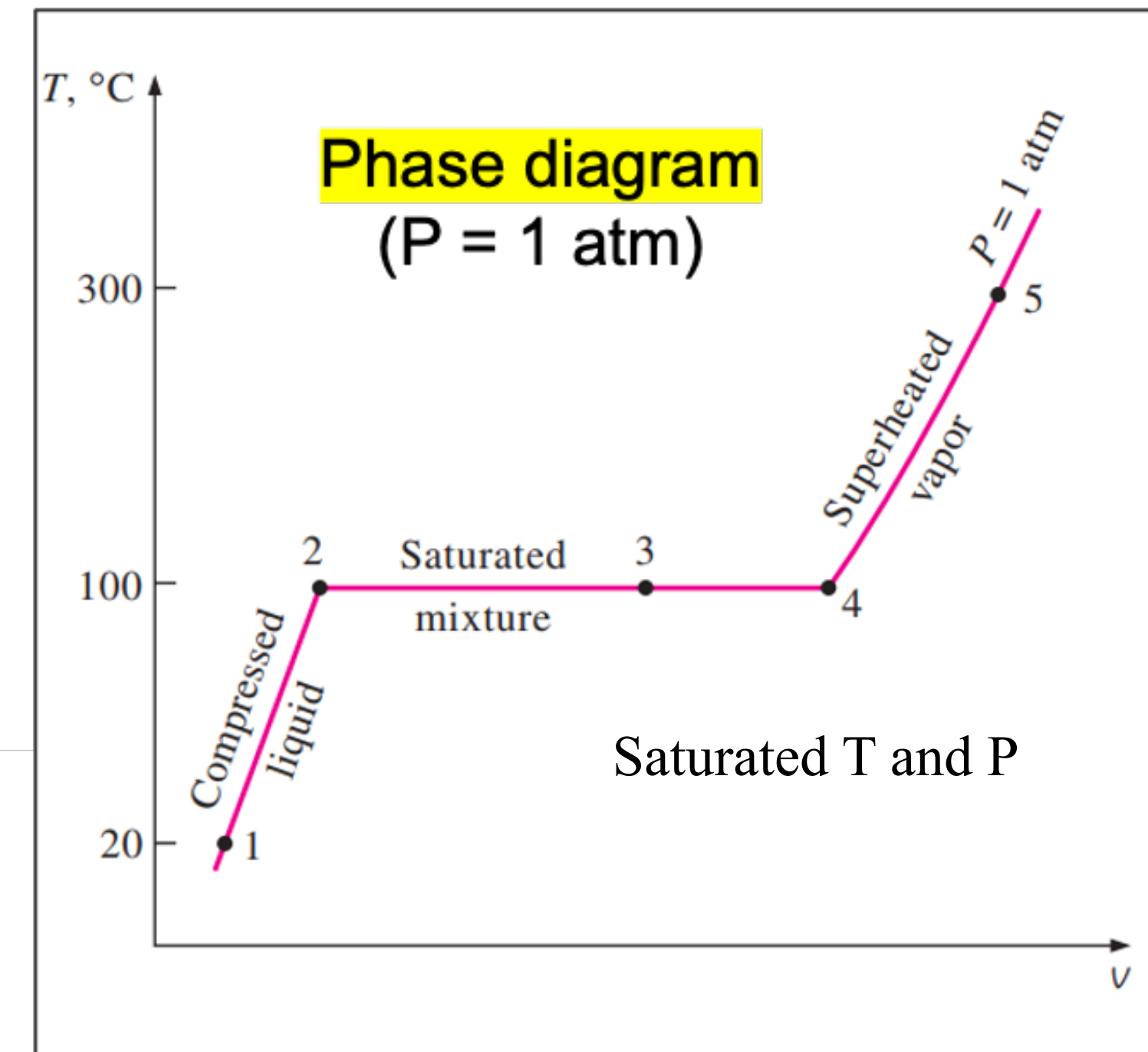
*saturated liquid–vapor mixture  
 [Property: Quality ( $x$ ) is used]*



*saturated vapor  
 (about to condense)*



*superheated vapor*



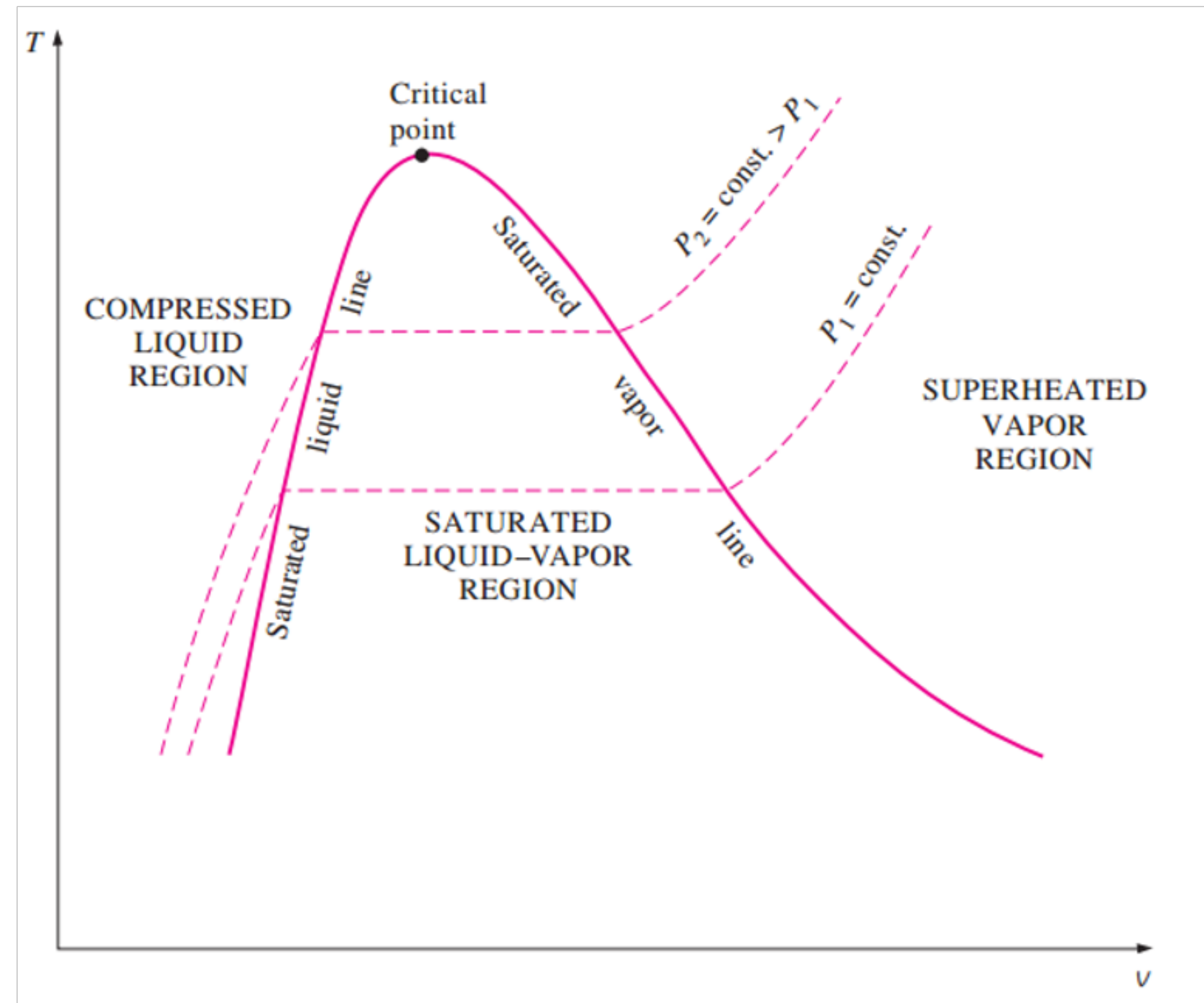
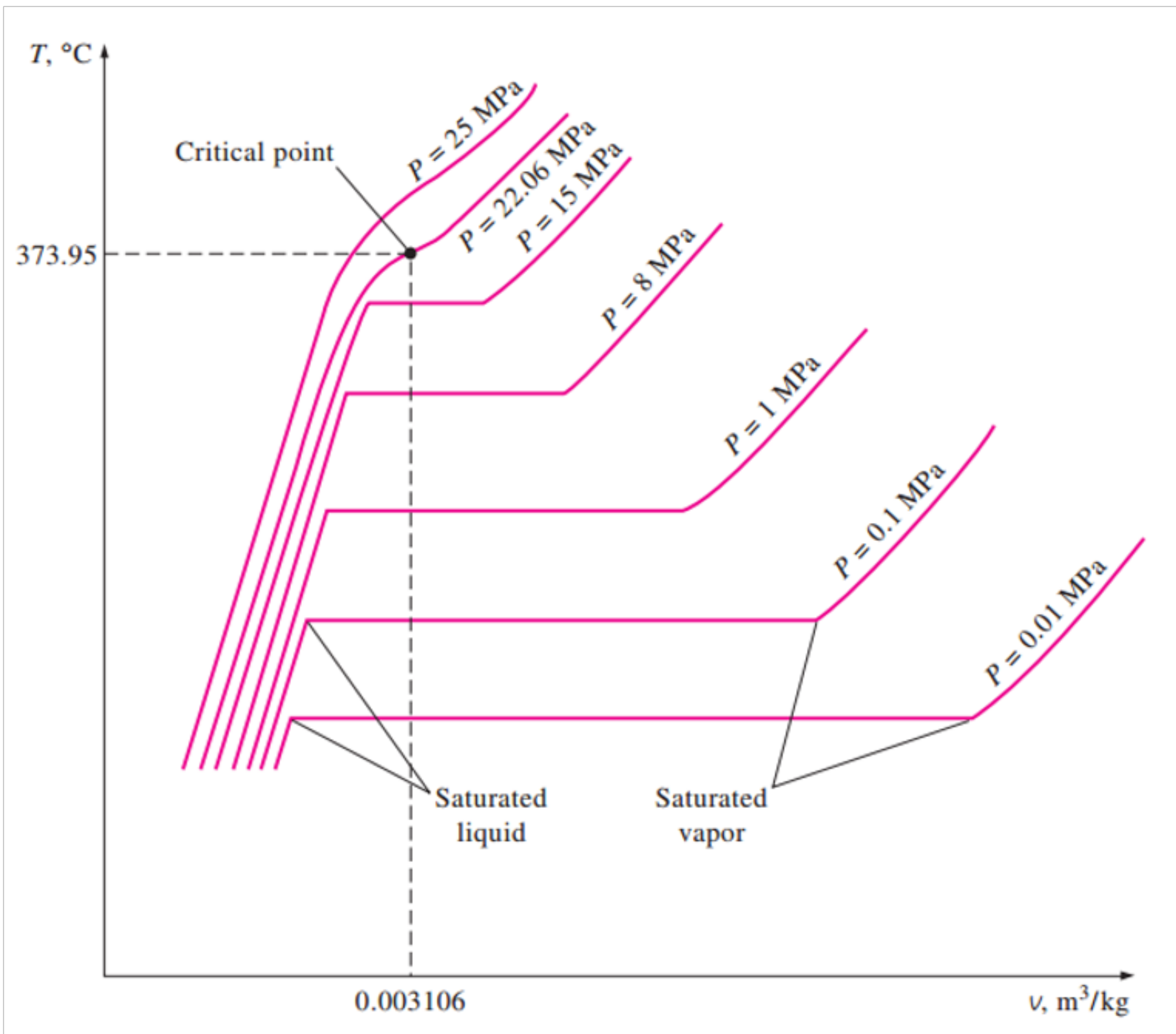
**Latent Heat:** Energy absorbed during phase change process

**Quality ( $x$ ):**  $0 \leq x \leq 1$   
 $x = 0$ : saturated liquid  
 $x = 1$ : saturated vapor

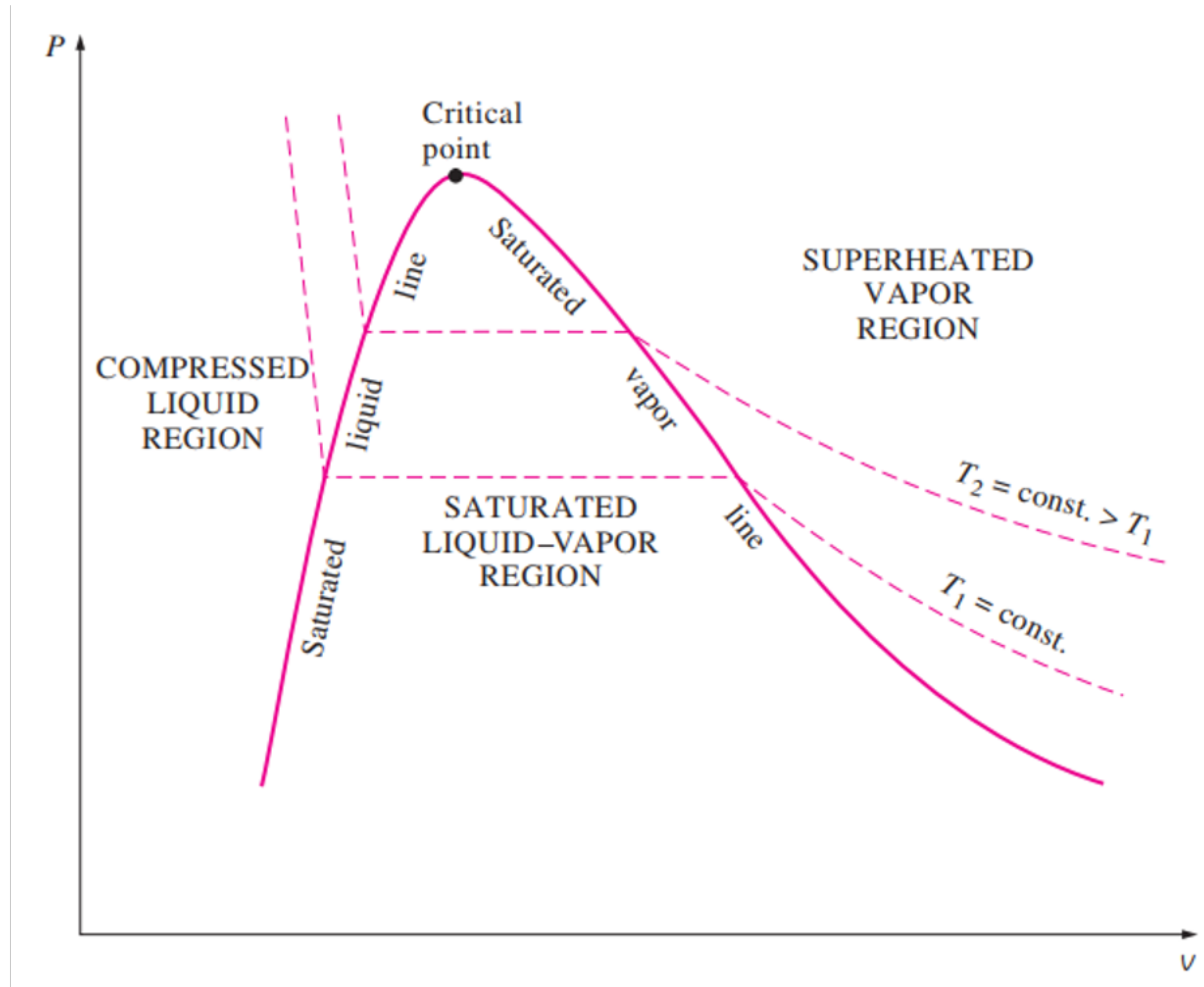
# Physical meaning of some terminology

- **Saturation temperature** designates the temperature at which vaporization takes place at a given pressure. This pressure is called the saturation pressure for the given temperature.
- If a substance exists as liquid at the saturation temperature and pressure, it is called a **saturated liquid**. If the temperature of the liquid is lower than the saturation temperature for the existing pressure, it is called either a **sub-cooled liquid** [implying  $T < T_{\text{sat}}$  (at a given  $P$ )] or a **compressed liquid**.
- When a substance exists as part liquid and part vapour at the saturation temperature, its **quality,  $x$**  is defined as the ratio of the mass of vapour to the total mass.
- If a substance exists as vapour at the saturation temperature, it is called **saturated vapour**. When the vapour is at a temperature greater than the saturation temperature, it is said to exist as **superheated vapour**.

# T-V diagram



# P-V diagram



# Enthalpy: a combinational property

- In the analysis of certain types of processes, particularly in power generation and refrigeration, we frequently encounter the combination of properties  $u$  (internal energy) and  $PV$  (pressure x volume).
- For the sake of simplicity and convenience, this combination is defined as a new property, ENTHALPY, and given the symbol  $H$  or  $h$ :

$$H = U + PV \text{ (kJ)}$$

$$h = u + PV \text{ (kJ/kg)}$$

# Saturated liquid and saturated vapor states

- **Table A-4:** Saturation properties of water under temperature.
- **Table A-5:** Saturation properties of water under pressure.

A partial list of Table A-4.

Temp. °C $T$	Sat. press. kPa $P_{sat}$	Specific volume $m^3/kg$	
		Sat. liquid $v_f$	Sat. vapor $v_g$
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Specific volume of saturated liquid

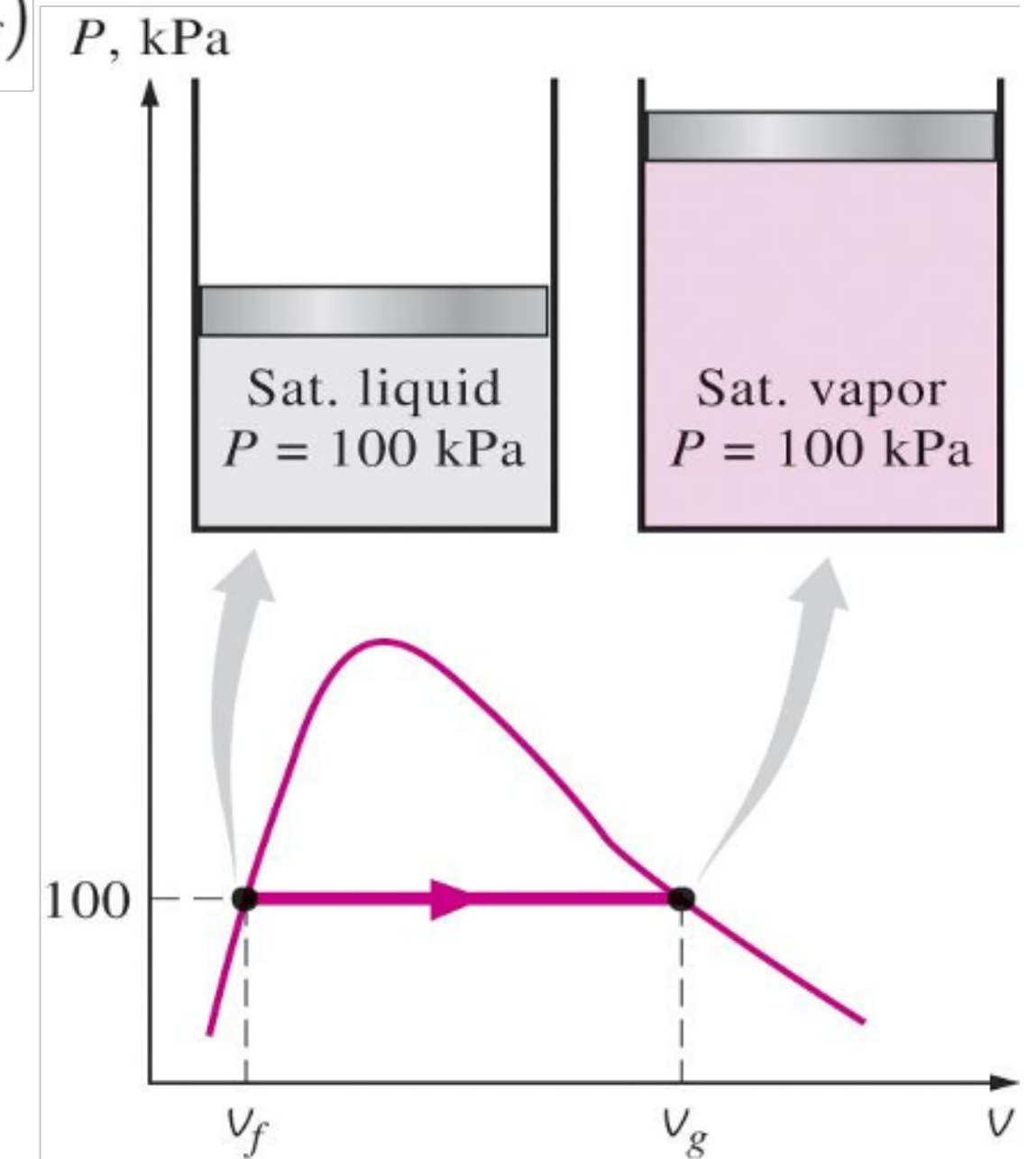
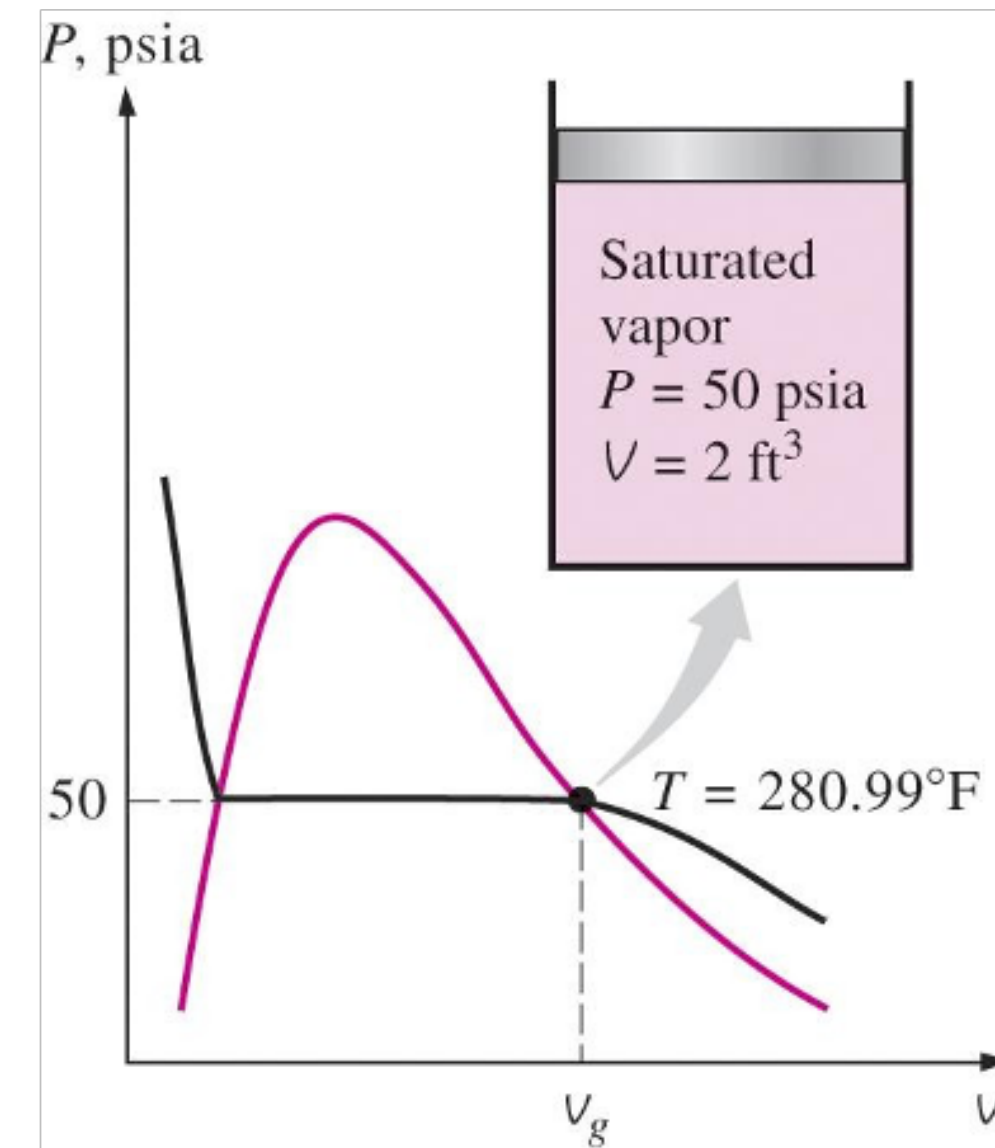
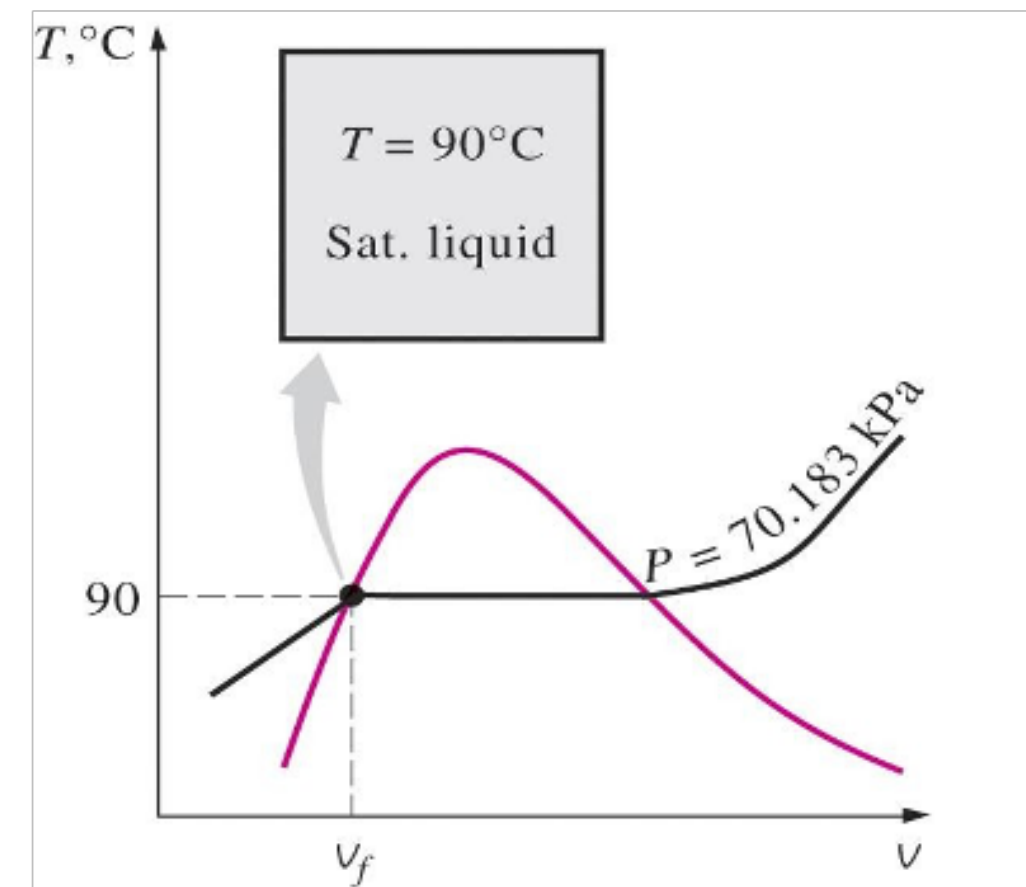
Corresponding saturation pressure

Specific volume of saturated vapor

$v_f$  = specific volume of saturated liquid

$v_g$  = specific volume of saturated vapor

$v_{fg}$  = difference between  $v_g$  and  $v_f$  (that is,  $v_{fg} = v_g - v_f$ )



# Saturated liquid-vapor mixture

**Quality,  $x$** : The ratio of the mass of vapor to the total mass of the mixture.

**Quality is between 0 and 1**      **0: sat. liquid, 1: sat. vapor.**

$$x = \frac{m_{\text{vapor}}}{m_{\text{total}}}$$

$$m_{\text{total}} = m_{\text{liquid}} + m_{\text{vapor}} = m_f + m_g$$

$$v_{\text{avg}} = v_f + xv_{fg} \quad (\text{m}^3/\text{kg})$$

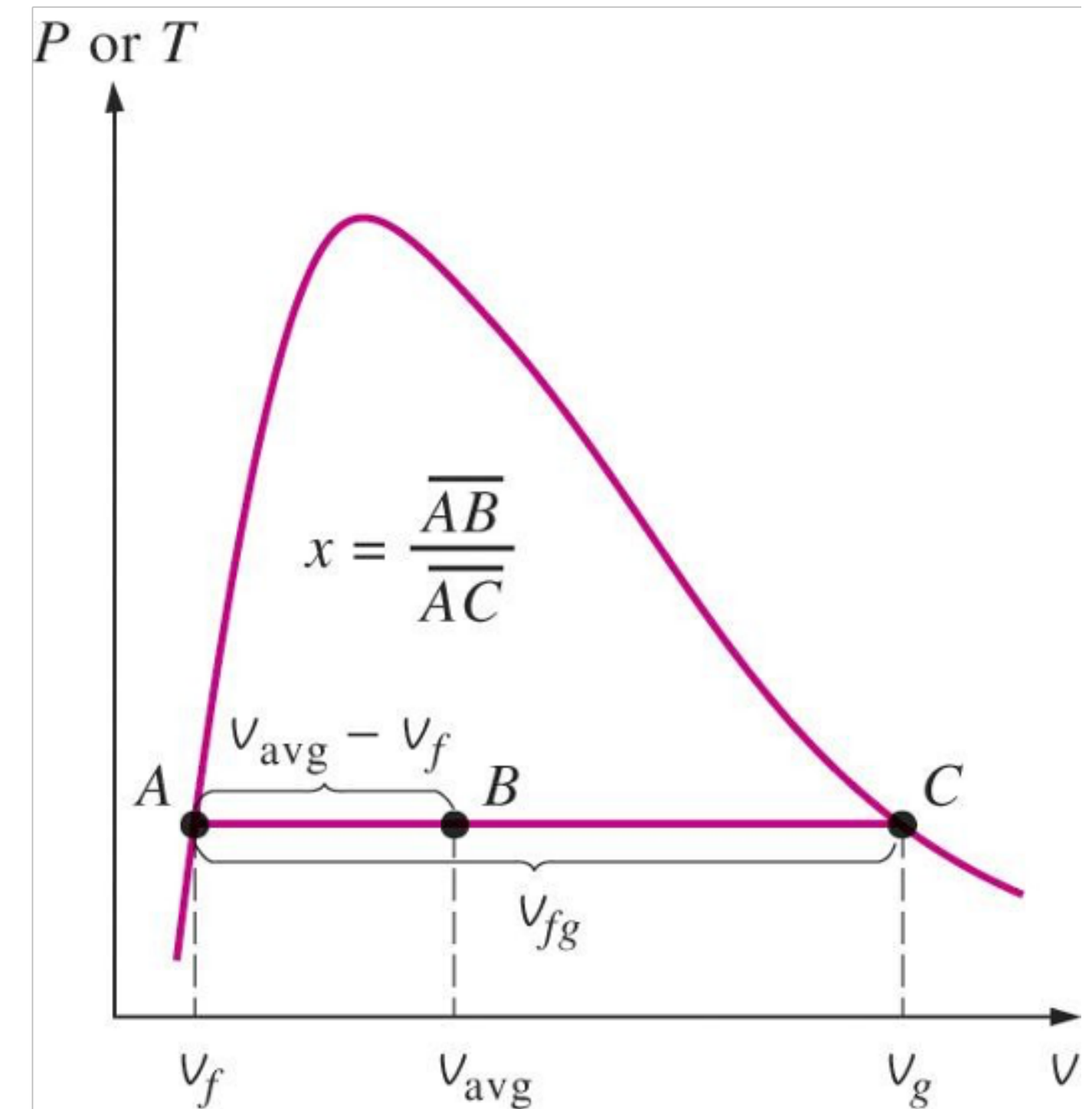
$$x = \frac{v_{\text{avg}} - v_f}{v_{fg}}$$

$$u_{\text{avg}} = u_f + xu_{fg} \quad (\text{kJ}/\text{kg})$$

$$y_{\text{avg}} = y_f + xy_{fg}$$

$$h_{\text{avg}} = h_f + xh_{fg} \quad (\text{kJ}/\text{kg})$$

$$y_f \leq y_{\text{avg}} \leq y_g$$



# Obtaining Data from a T<sub>sat</sub> Table

TABLE A-4

Saturated water—Temperature table

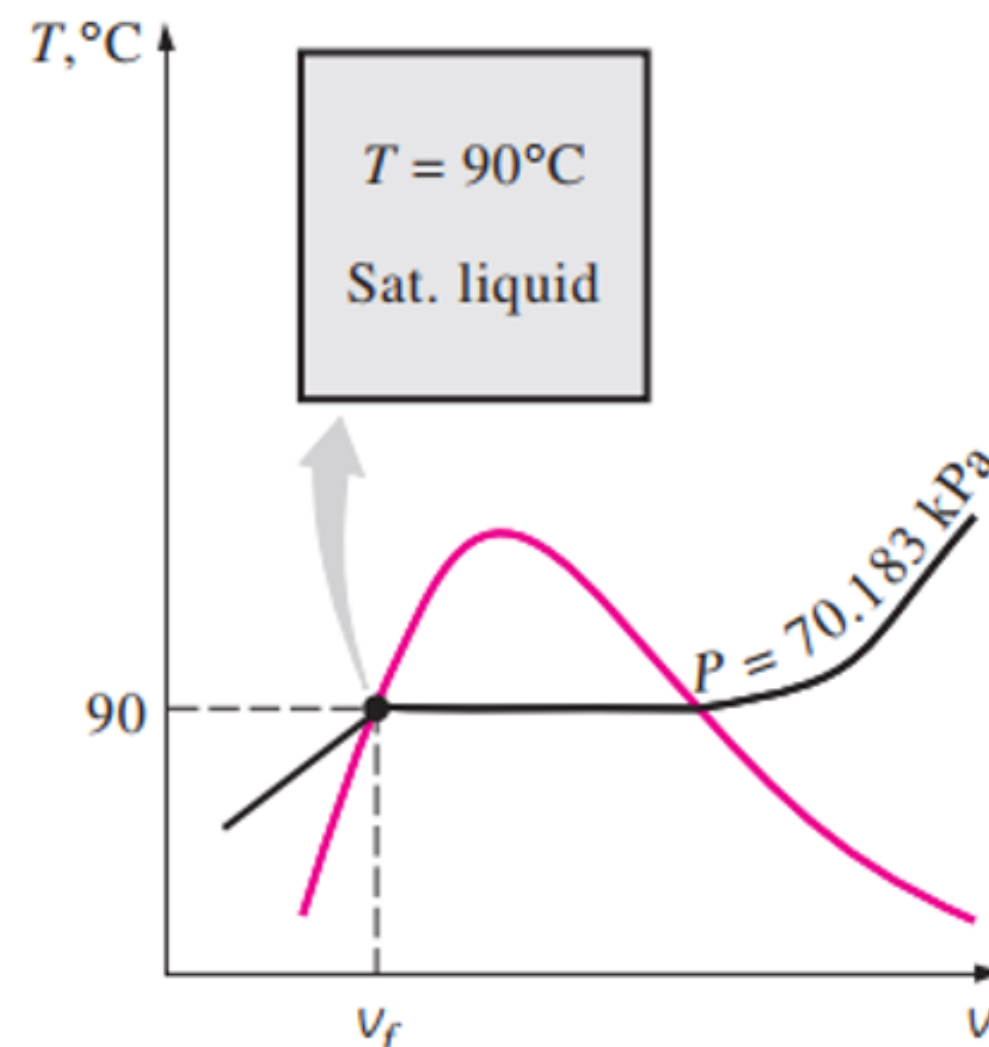
Temp., <i>T</i> °C	Sat. press., <i>P</i> <sub>sat</sub> kPa	Specific volume, m <sup>3</sup> /kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, <i>v</i> <sub>f</sub>	Sat. vapor, <i>v</i> <sub>g</sub>	Sat. liquid, <i>u</i> <sub>f</sub>	Evap., <i>u</i> <sub>fg</sub>	Sat. vapor, <i>u</i> <sub>g</sub>	Sat. liquid, <i>h</i> <sub>f</sub>	Evap., <i>h</i> <sub>fg</sub>	Sat. vapor, <i>h</i> <sub>g</sub>	Sat. liquid, <i>s</i> <sub>f</sub>	Evap., <i>s</i> <sub>fg</sub>	Sat. vapor, <i>s</i> <sub>g</sub>
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151

# Obtaining Data from a P\_sat Table

**TABLE A-5**

Saturated water—Pressure table

Press., <i>P</i> kPa	Sat. temp., <i>T</i> <sub>sat</sub> °C	Specific volume, m <sup>3</sup> /kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, <i>v</i> <sub>f</sub>	Sat. vapor, <i>v</i> <sub>g</sub>	Sat. liquid, <i>u</i> <sub>f</sub>	Evap., <i>u</i> <sub>fg</sub>	Sat. vapor, <i>u</i> <sub>g</sub>	Sat. liquid, <i>h</i> <sub>f</sub>	Evap., <i>h</i> <sub>fg</sub>	Sat. vapor, <i>h</i> <sub>g</sub>	Sat. liquid, <i>s</i> <sub>f</sub>	Evap., <i>s</i> <sub>fg</sub>	Sat. vapor, <i>s</i> <sub>g</sub>
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931



**FIGURE 3–31**  
Schematic and  $T$ - $v$  diagram for Example 3–1.

**EXAMPLE 3–1 Pressure of Saturated Liquid in a Tank**

A rigid tank contains 50 kg of saturated liquid water at 90°C. Determine the pressure in the tank and the volume of the tank.

**Solution** A rigid tank contains saturated liquid water. The pressure and volume of the tank are to be determined.

**Analysis** The state of the saturated liquid water is shown on a  $T$ - $v$  diagram in Fig. 3–31. Since saturation conditions exist in the tank, the pressure must be the saturation pressure at 90°C:

$$P = P_{\text{sat @ } 90^\circ\text{C}} = \mathbf{70.183 \text{ kPa}} \quad (\text{Table A–4})$$

The specific volume of the saturated liquid at 90°C is

$$v = v_{f @ 90^\circ\text{C}} = 0.001036 \text{ m}^3/\text{kg} \quad (\text{Table A–4})$$

Then the total volume of the tank becomes

$$V = m v = (50 \text{ kg})(0.001036 \text{ m}^3/\text{kg}) = \mathbf{0.0518 \text{ m}^3}$$

**TABLE A–4**

Saturated water—Temperature table

Temp., $T$ °C	Sat. press., $P_{\text{sat}}$ kPa	Specific volume, $\text{m}^3/\text{kg}$		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, $v_f$	Sat. vapor, $v_g$	Sat. liquid, $u_f$	Evap., $u_{fg}$	Sat. vapor, $u_g$	Sat. liquid, $h_f$	Evap., $h_{fg}$	Sat. vapor, $h_g$	Sat. liquid, $s_f$	Evap., $s_{fg}$	Sat. vapor, $s_g$
90	70.183	0.001036	1.6471	376.87	2088.7	2465.6	376.87	2088.7	2465.6	1.1453	2.2471	3.3924

# R-134a property table

A **refrigerant** is a chemical substance used in refrigerator and air conditioning systems.

**TABLE A-12**

Saturated refrigerant-134a—Pressure table

Press., $P$ kPa	Sat. temp., $T_{\text{sat}}$ °C	Specific volume, $\text{m}^3/\text{kg}$		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, $v_f$	Sat. vapor, $v_g$	Sat. liquid, $u_f$	Evap., $u_{fg}$	Sat. vapor, $u_g$	Sat. liquid, $h_f$	Evap., $h_{fg}$	Sat. vapor, $h_g$	Sat. liquid, $s_f$	Evap., $s_{fg}$	Sat. vapor, $s_g$
60	-36.95	0.0007098	0.31121	3.798	205.32	209.12	3.841	223.95	227.79	0.01634	0.94807	0.96441
70	-33.87	0.0007144	0.26929	7.680	203.20	210.88	7.730	222.00	229.73	0.03267	0.92775	0.96042
80	-31.13	0.0007185	0.23753	11.15	201.30	212.46	11.21	220.25	231.46	0.04711	0.90999	0.95710
90	-28.65	0.0007223	0.21263	14.31	199.57	213.88	14.37	218.65	233.02	0.06008	0.89419	0.95427
100	-26.37	0.0007259	0.19254	17.21	197.98	215.19	17.28	217.16	234.44	0.07188	0.87995	0.95183
120	-22.32	0.0007324	0.16212	22.40	195.11	217.51	22.49	214.48	236.97	0.09275	0.85503	0.94779
140	-18.77	0.0007383	0.14014	26.98	192.57	219.54	27.08	212.08	239.16	0.11087	0.83368	0.94456
160	-15.60	0.0007437	0.12348	31.09	190.27	221.35	31.21	209.90	241.11	0.12693	0.81496	0.94190
180	-12.73	0.0007487	0.11041	34.83	188.16	222.99	34.97	207.90	242.86	0.14139	0.79826	0.93965
200	-10.09	0.0007533	0.099867	38.28	186.21	224.48	38.43	206.03	244.46	0.15457	0.78316	0.93773

### EXAMPLE 3–5 Properties of Saturated Liquid–Vapor Mixture

An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa. Determine (a) the temperature, (b) the quality, (c) the enthalpy of the refrigerant, and (d) the volume occupied by the vapor phase.

$$v = \frac{V}{m} = \frac{0.080 \text{ m}^3}{4 \text{ kg}} = 0.02 \text{ m}^3/\text{kg}$$

At 160 kPa, we read

$$\begin{aligned}v_f &= 0.0007437 \text{ m}^3/\text{kg} \\v_g &= 0.12348 \text{ m}^3/\text{kg}\end{aligned}\quad (\text{Table A-12})$$

Obviously,  $v_f < v < v_g$ , and, the refrigerant is in the saturated mixture region. Thus, the temperature must be the saturation temperature at the specified pressure:

$$T = T_{\text{sat @ 160 kPa}} = -15.60^\circ\text{C}$$

(b) Quality can be determined from

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.02 - 0.0007437}{0.12348 - 0.0007437} = 0.157$$

### EXAMPLE 3–5 Properties of Saturated Liquid–Vapor Mixture

An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa. Determine (a) the temperature, (b) the quality, (c) the enthalpy of the refrigerant, and (d) the volume occupied by the vapor phase.

(c) At 160 kPa, we also read from Table A–12 that  $h_f = 31.21$  kJ/kg and  $h_{fg} = 209.90$  kJ/kg. Then,

$$\begin{aligned}h &= h_f + xh_{fg} \\ &= 31.21 \text{ kJ/kg} + (0.157)(209.90 \text{ kJ/kg}) \\ &= \mathbf{64.2 \text{ kJ/kg}}\end{aligned}$$

(d) The mass of the vapor is

$$m_g = xm_t = (0.157)(4 \text{ kg}) = 0.628 \text{ kg}$$

and the volume occupied by the vapor phase is

$$V_g = m_g v_g = (0.628 \text{ kg})(0.12348 \text{ m}^3/\text{kg}) = \mathbf{0.0775 \text{ m}^3} \text{ (or 77.5 L)}$$

The rest of the volume (2.5 L) is occupied by the liquid.

# Obtaining Data From a Superheated vapor Table

**TABLE A-6**

Superheated water

$T$ °C	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg·K	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg·K	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg·K
$P = 0.01 \text{ MPa (45.81°C)*}$					$P = 0.05 \text{ MPa (81.32°C)}$				$P = 0.10 \text{ MPa (99.61°C)}$			
Sat.†	14.670	2437.2	2583.9	8.1488	3.2403	2483.2	2645.2	7.5931	1.6941	2505.6	2675.0	7.3589
50	14.867	2443.3	2592.0	8.1741								
100	17.196	2515.5	2687.5	8.4489	3.4187	2511.5	2682.4	7.6953	1.6959	2506.2	2675.8	7.3611
150	19.513	2587.9	2783.0	8.6893	3.8897	2585.7	2780.2	7.9413	1.9367	2582.9	2776.6	7.6148
200	21.826	2661.4	2879.6	8.9049	4.3562	2660.0	2877.8	8.1592	2.1724	2658.2	2875.5	7.8356
250	24.136	2736.1	2977.5	9.1015	4.8206	2735.1	2976.2	8.3568	2.4062	2733.9	2974.5	8.0346
300	26.446	2812.3	3076.7	9.2827	5.2841	2811.6	3075.8	8.5387	2.6389	2810.7	3074.5	8.2172
400	31.063	2969.3	3280.0	9.6094	6.2094	2968.9	3279.3	8.8659	3.1027	2968.3	3278.6	8.5452
500	35.680	3132.9	3489.7	9.8998	7.1338	3132.6	3489.3	9.1566	3.5655	3132.2	3488.7	8.8362
600	40.296	3303.3	3706.3	10.1631	8.0577	3303.1	3706.0	9.4201	4.0279	3302.8	3705.6	9.0999
700	44.911	3480.8	3929.9	10.4056	8.9813	3480.6	3929.7	9.6626	4.4900	3480.4	3929.4	9.3424
800	49.527	3665.4	4160.6	10.6312	9.9047	3665.2	4160.4	9.8883	4.9519	3665.0	4160.2	9.5682
900	54.143	3856.9	4398.3	10.8429	10.8280	3856.8	4398.2	10.1000	5.4137	3856.7	4398.0	9.7800
1000	58.758	4055.3	4642.8	11.0429	11.7513	4055.2	4642.7	10.3000	5.8755	4055.0	4642.6	9.9800
1100	63.373	4260.0	4893.8	11.2326	12.6745	4259.9	4893.7	10.4897	6.3372	4259.8	4893.6	10.1698
1200	67.989	4470.9	5150.8	11.4132	13.5977	4470.8	5150.7	10.6704	6.7988	4470.7	5150.6	10.3504
1300	72.604	4687.4	5413.4	11.5857	14.5209	4687.3	5413.3	10.8429	7.2605	4687.2	5413.3	10.5229

Find specific volume( $v$ ), specific enthalpy( $h$ ), specific internal energy( $u$ ) and specific entropy( $s$ ) of water at  $T=400^\circ\text{C}$  and  $P= 50 \text{ kPa}$

# Reading material

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- Cengel: Chapter 2 and 3