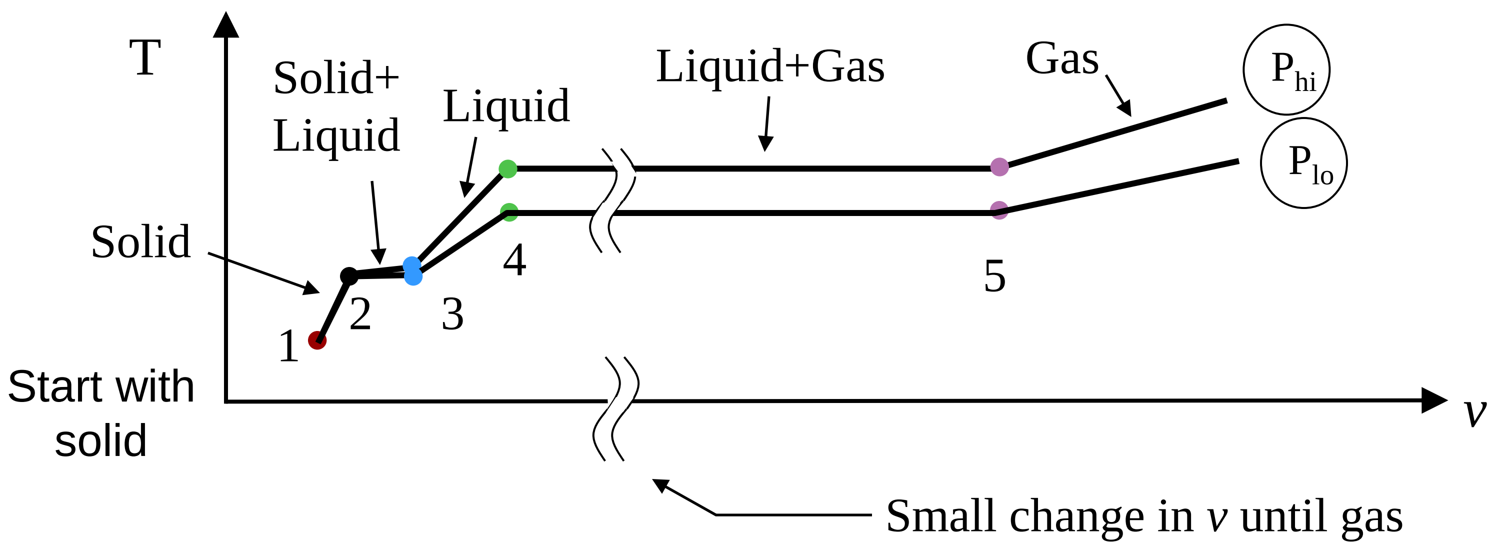
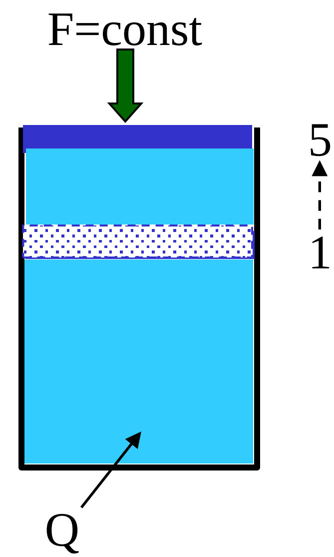
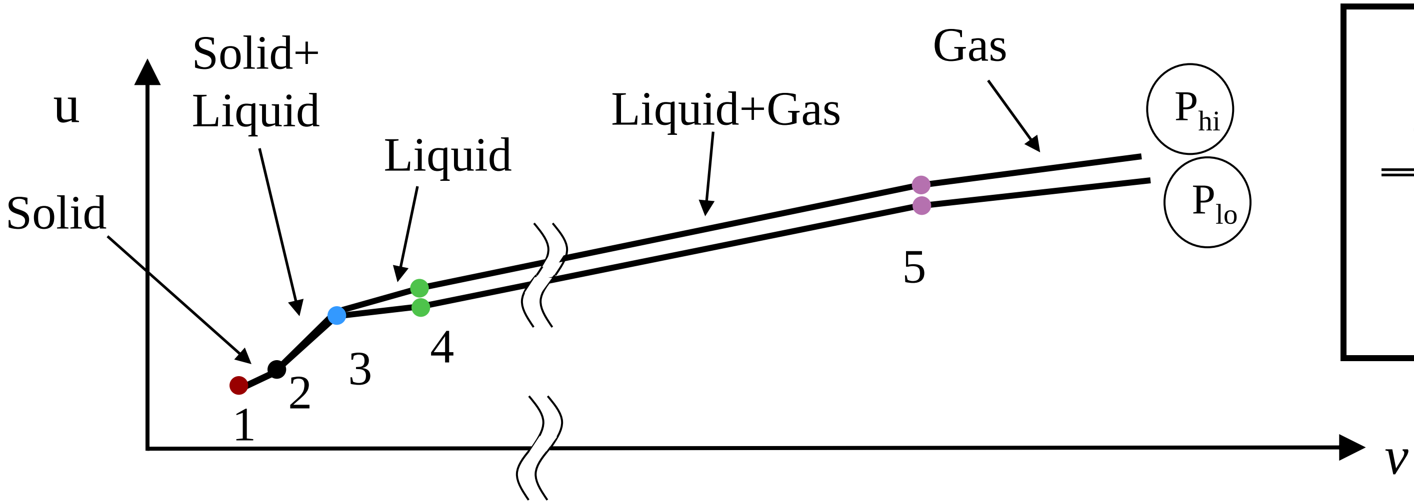
Equilibrium Diagrams and Saturated Liquid/Vapor Systems

- In equilibrium, different phases of matter
  - gas, liquid, solid (also multiple solid phases, e.g., different crystalline structures of steel)
- So far looked at individual phases of simple (homogeneous) substances
- Multiple phases can exist simultaneously in equilibrium
- Consider heating simple compressible substance at constant pressure

Phase Transitions - Constant Pressure



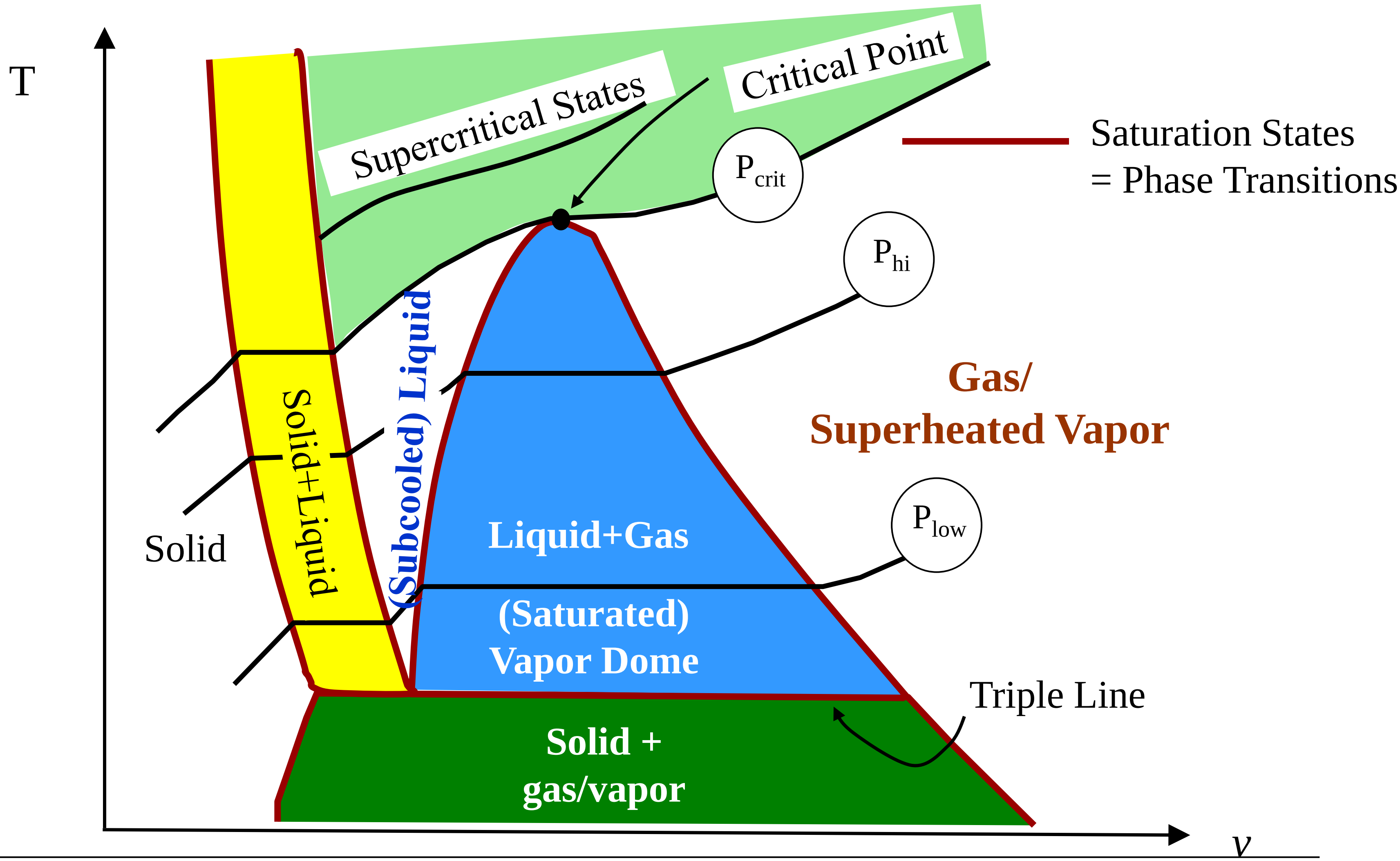




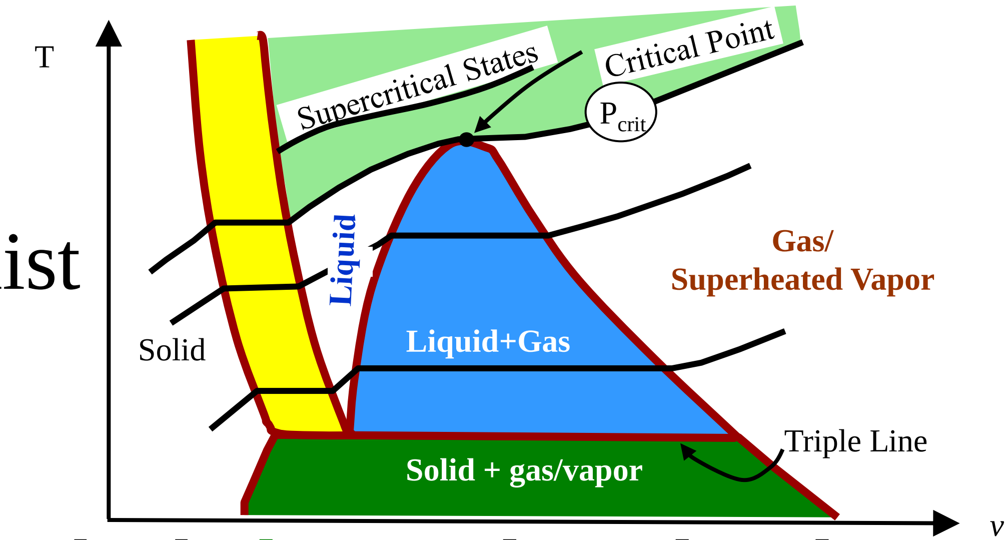
2→3: Melting
4 →5: Evaporation

3→2: Freezing/Fusion
5 →4: Condensation

Typical T-*v* Diagram



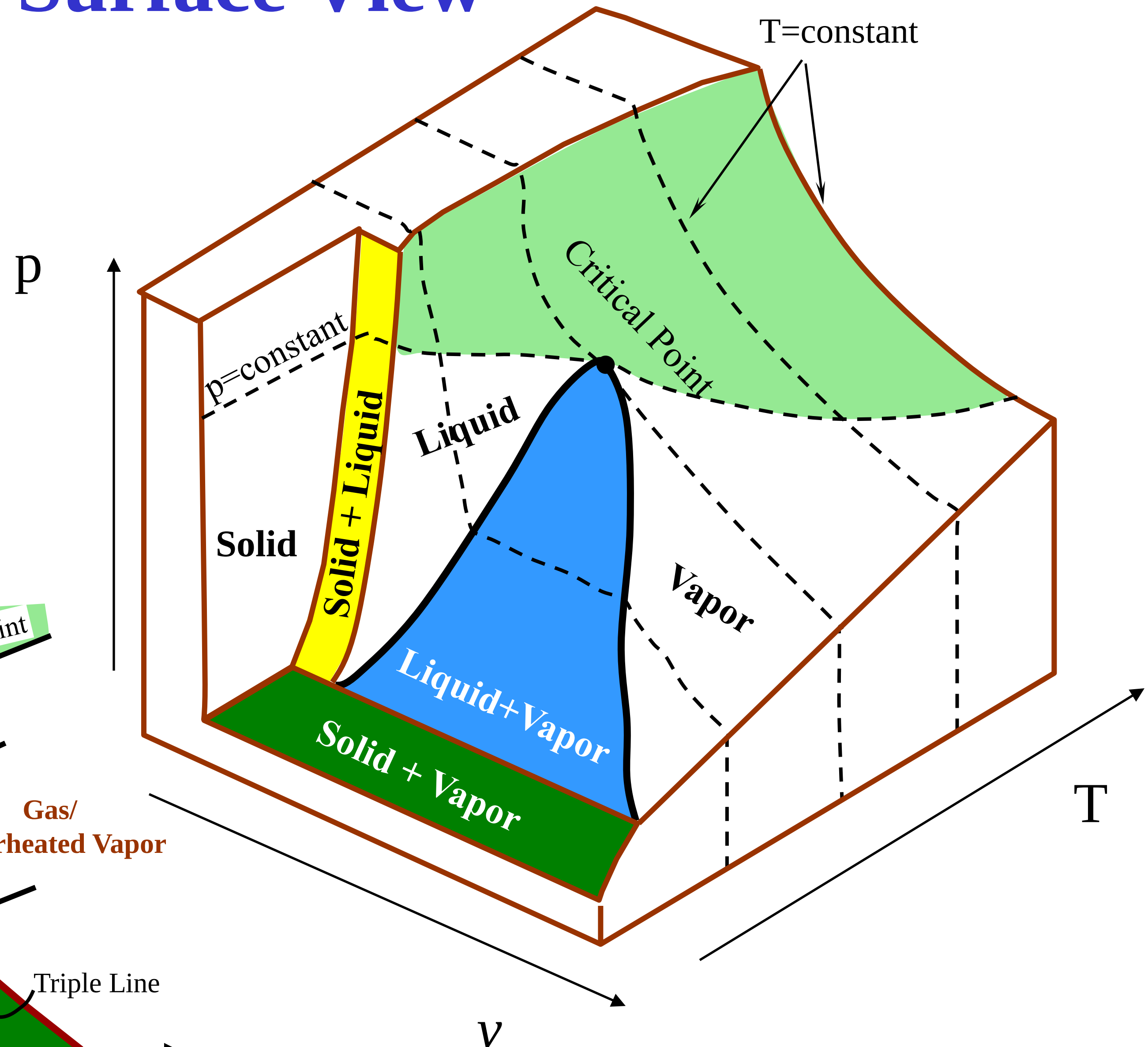
Phases of Compressible Substances

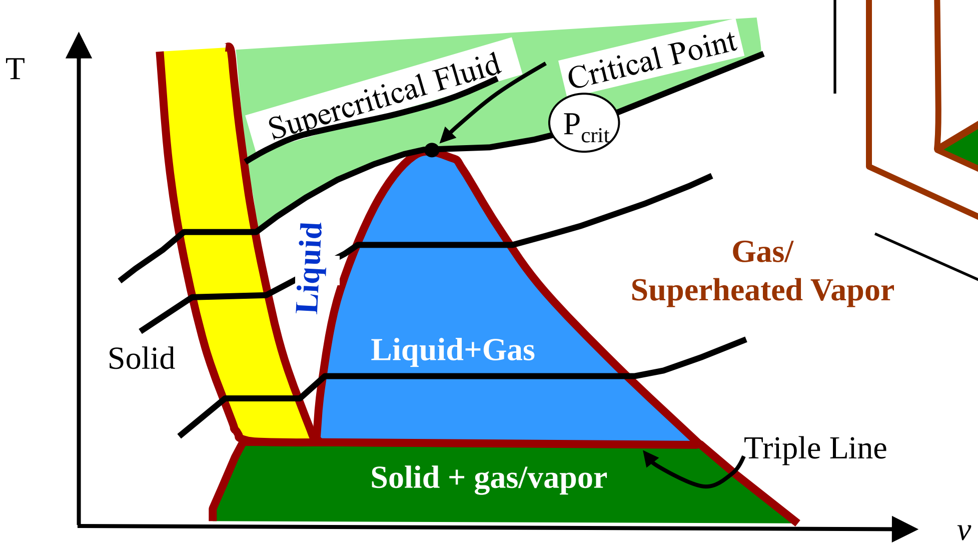


- Triple Line
  - all 3 phases can coexist at same T and P
- Critical Point
  - maximum T and p at which distinct liquid and gas phases can coexist
- Supercritical States (or supercritical fluid)
  - for $p>p_{crit}$), no distinct transition from liquid to gas, fluid can have characteristics of both

Surface View

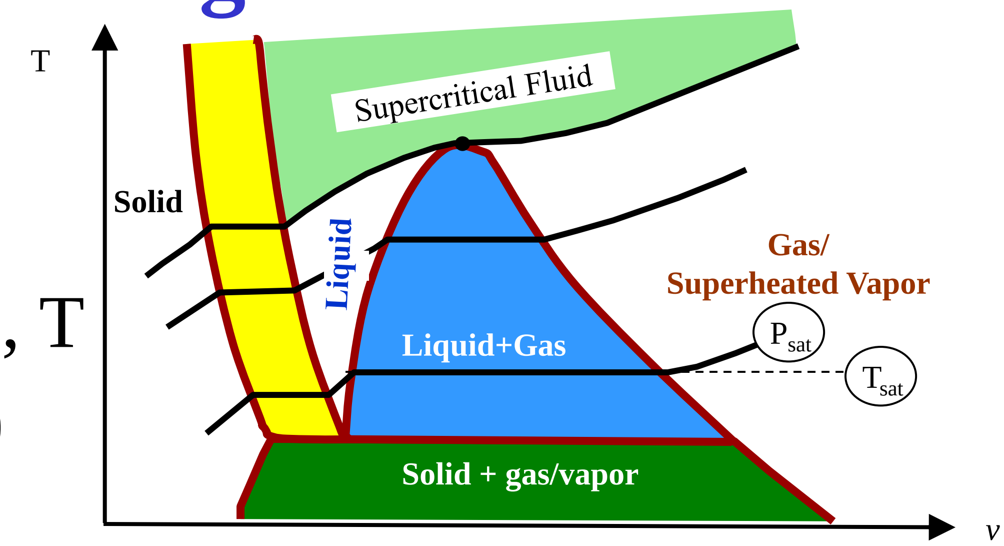
- Phase space not just 2 dimensional

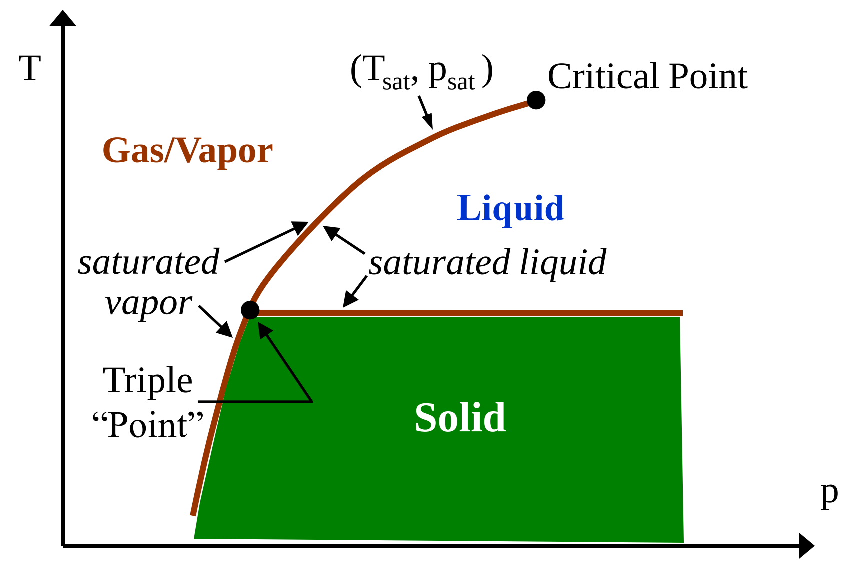




Mixed Phase Regions

- Independent TD properies
  - p and T not independent
  - phase transition at const. p, T (e.g., given T_{sat}, know p_{sat})
- Can define new intensitive variable to characterize composition
  - describe how much of each phase present
  - should not depend on total mass





Quality of Saturated Liquid-Vapor

- For saturated liquid-vapor region (vapor dome)
  - new variable is quality, x

$$x \equiv \frac{m_g}{m_{mixture}} = \frac{m_g}{m_f + m_g}$$

  - x gives fraction of mass that is gas (g) — **vapor mass fraction, Y_v**
  - (1-x) is fraction of mass that is liquid (f) — **liquid mass fraction, Y_l**
  - $0 < x < 1$ (0 for liquid, 1 for gas)

Volume of Saturated Liquid-Vapor Mixture

- Get TD properties of saturated mixture by summing up proper amount of property for each phase, e.g.,

$$V_{mix} = m_g v_g + m_f v_f = m_{mix}\left[\frac{m_g v_g}{m_{mix}} + \frac{m_f v_f}{m_{mix}}\right]$$

$$= m_{mix}\left[x v_g + (1-x) v_f\right]$$

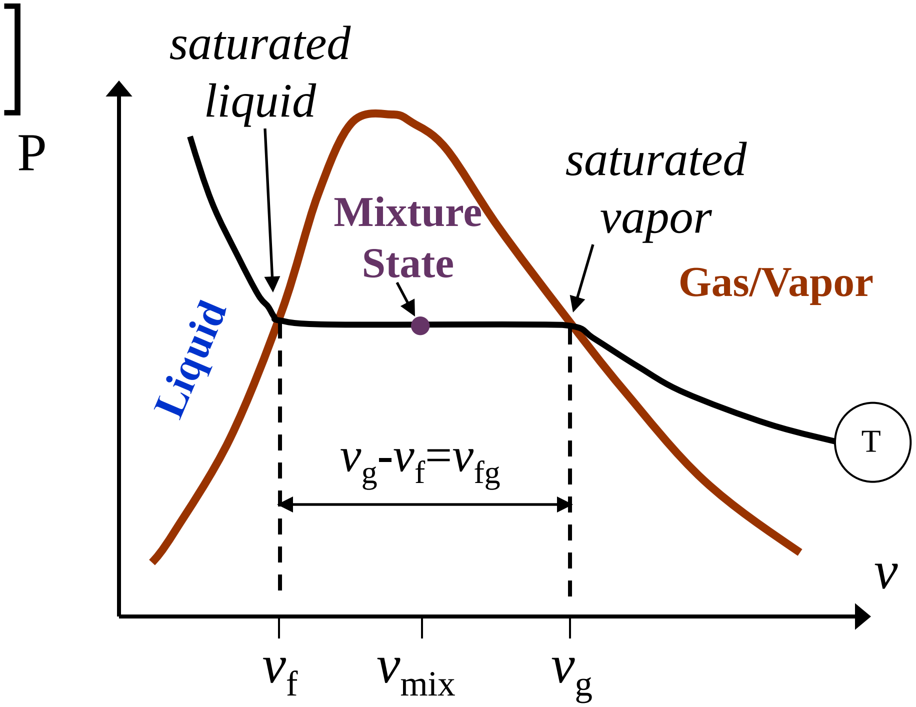
or

$$v_{mix} = x v_g + (1-x) v_f$$

$$= v_f + x\left(v_g - v_f\right)$$

– where

g→gas, f → liquid



Saturated Liquid-Vapor Mixture Properties

- For general intensive property ***y*** that obeys sum rule,

$$y_{mix} = x y_g + (1-x) y_f$$

or

$$y_{mix} = y_f + x\, y_{fg}$$

with $y_{fg} \equiv y_g - y_f$

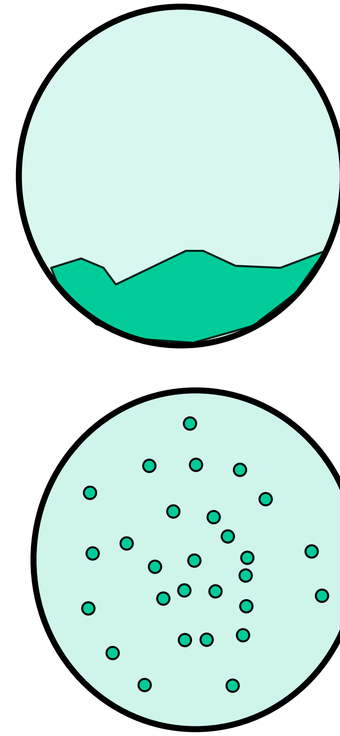
– y_{mix} always bounded by y_f , y_g

– does not work for ρ ($\rho \neq \rho_1 + \rho_2$)

Does T_{mix} obey sum rule?

Example 1:

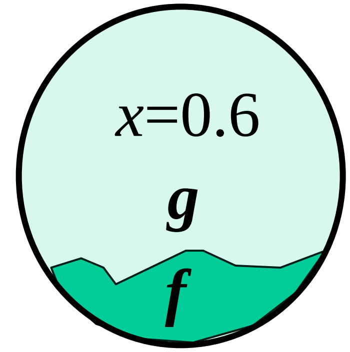
- **Given:** 3 kg of water at 200°C with quality x=0.6
- **Find:** Volume (V) and internal energy (U)
- **Assume:** phase equilibrium



Example 1:

m=3 kg

T=200°C



- **Analysis:**

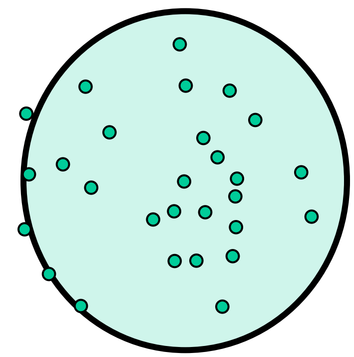
$$V = m\left[v_f + x v_{fg}\right]$$

Table B.1

$$= 3kg\left[0.0011564 + 0.6(0.1262)\right]\frac{m^3}{kg}$$

$$= 3kg\left[0.07688\, m^3/kg\right]$$

$$= 0.231 m^3$$



Note: v_{mix}>>v_f (~70×)

because v_g>>v_f

or ρ_g<<ρ_f

$$U = m\left[u_f + x u_{fg}\right]$$

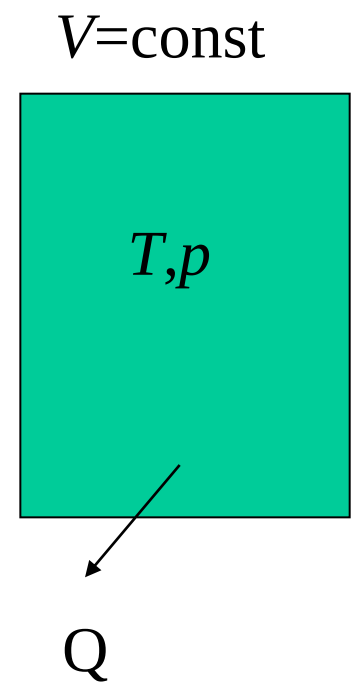
$$= 3kg\left[850.58 + 0.6(1744.1)\right] kJ/kg$$

u_g only ~3×u_f

$$= 5691 kJ$$

What is pressure of mixture?

Example 2:



- **Given:** 5 lb_m of water initially at 700°F and 2000 psia in rigid container
- **Find:** How much energy loss required to cool water to 300°F
- **Assume:** equilibrium initial and final state
- **Analysis:**

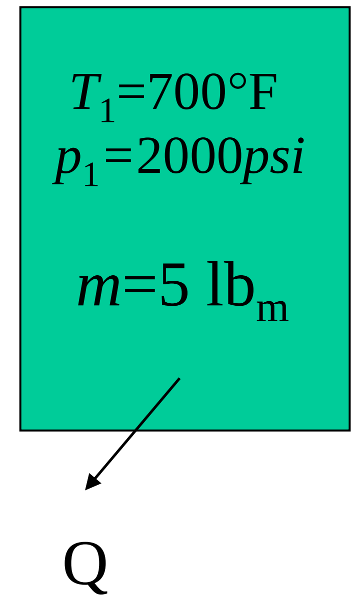
$p\,dV=0$

$$Q = \Delta U = m(u_1 - u_2)$$

Need u_2 and u_1

Example 2:

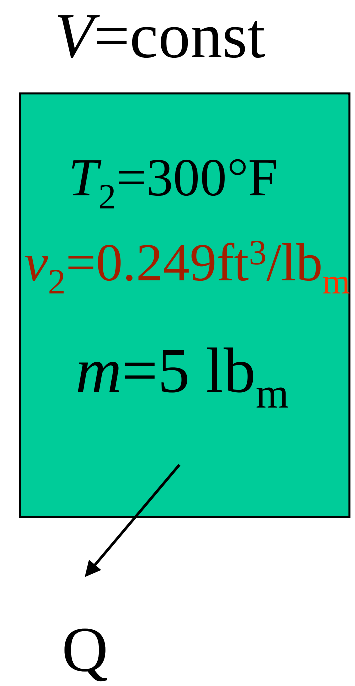
V=const



- $\boldsymbol{u_1}$**=?**
- $T > T_{sat}$
  - –superheated vapor

$\boldsymbol{u_1}$=1147.2 BTU/lb_m

Example 2:



$$v_2 = v_f + x_2 v_{fg}$$

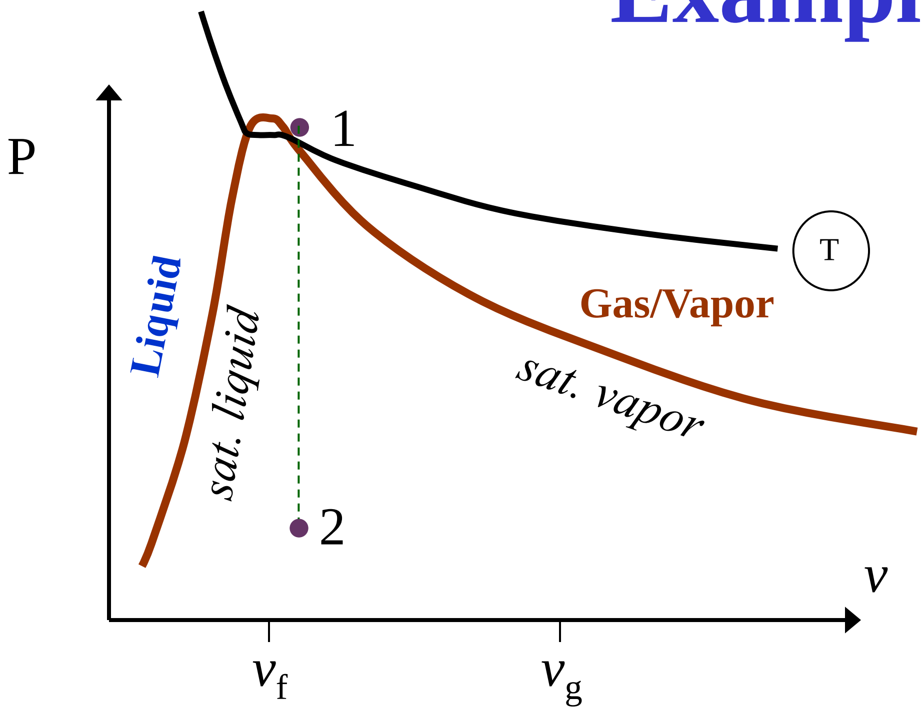
$$u_2 = \qquad = 299\,BTU/lb_m$$

$$\Delta U = m(u_1 - u_2) = Q$$

$$=$$

$$= 4240\,BTU\,(4.47\,MJ)$$

Example 2:



V=const

State 1	State 2
T_1=700°F	T_2=300°F
p_1=2000*psi*	p_2=66.97*psi*
v_1=0.25ft^3/lb_m	v_2=0.25ft^3/lb_m
m=5 lb_m	m=5 lb_m

- Do phases always coexist in equilibrium?