EPFL

ETA-Lab
Energy Transport Advances

# ME-251: Thermodynamics and energetics I
# First Law of Thermodynamics II


Zhengmao Lu

Energy Transport Advances Laboratory

EPFL Mechanical Engineering


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Photo Credit: Trougnouf

# Last Time

- Explain key concepts in the first law of thermodynamics
  - Energy change $\Delta E = \Delta KE + \Delta PE + \Delta U$
  - Work (Work done by the system)
  - Heat (Heat received by the system)

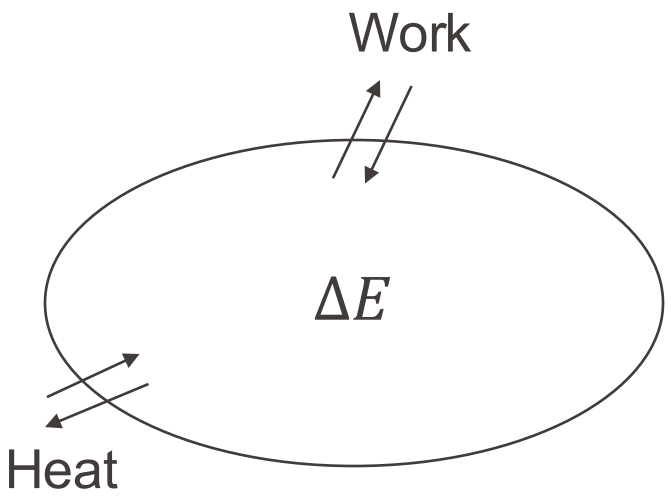
# ILOs for Today

- Apply energy balance to closed systems
- Analyze the energy balance of thermodynamic cycles
- Understand and interpret equation of state (p-T-v surface)

- Reading materials: **Moran** 2.1-2.4

# First Law of Thermodynamics (Intuition)





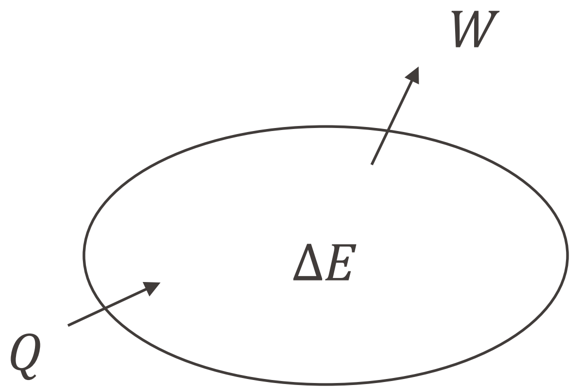

Can be intuitively understood as energy conservation

Energy change = Energy going in – Energy going out

Energy flows can take the form of heat, work, …

# First Law of Thermodynamics for a Closed System

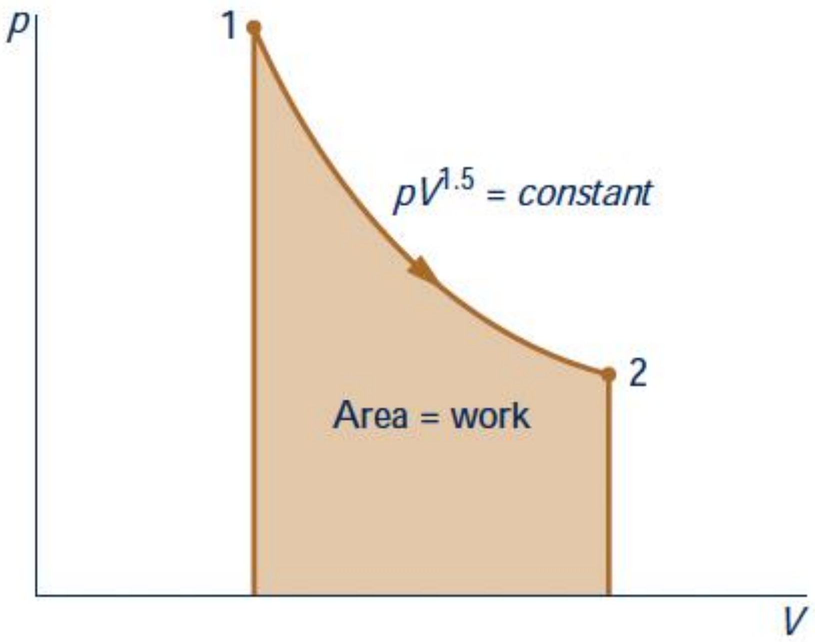
| Change in the amount of energy contained within a system during some time interval | = | Net amount of energy transferred **into** the system by heat transfer during the time interval | − | Net amount of energy transferred **out of** the system by work during the time interval |
|---|---|---|---|---|
| | | | or + | Net amount of energy transferred **into** the system by work during the time interval |

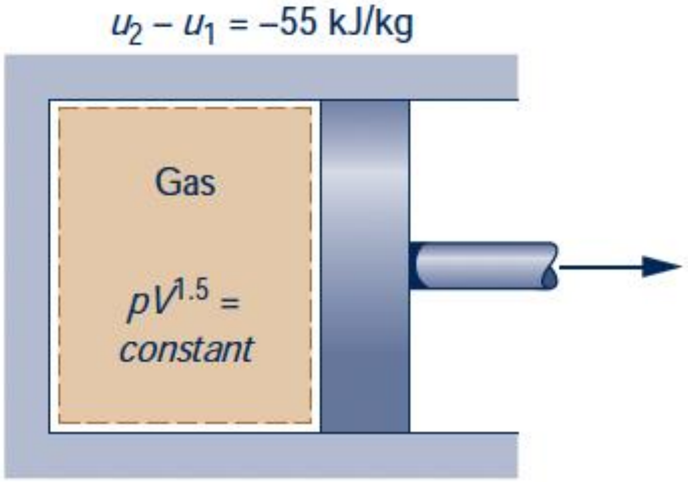



$$\Delta E = E_2 - E_1 = Q - W$$

Everything here is in [J]

# Example 2.2 in Moran



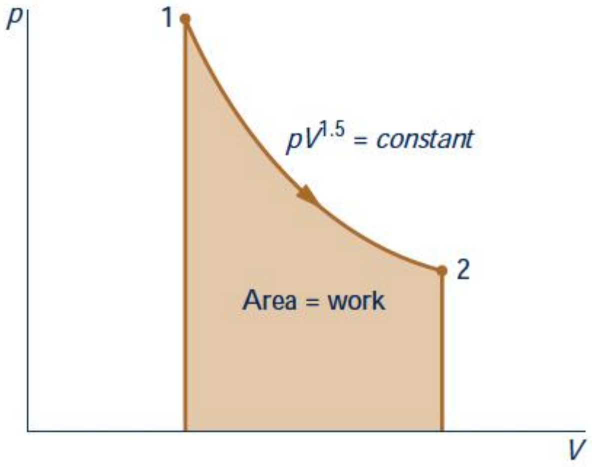



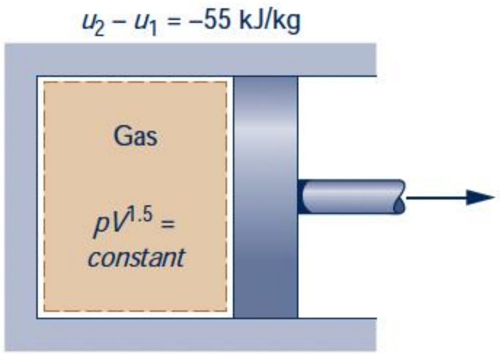

Gas expansion: $V_1 = 0.1\ \mathrm{m}^3$, $p_1 = 3\ \mathrm{bar}$; $V_2 = 0.2\ \mathrm{m}^3$; $pV^{1.5} = \mathrm{const}$, $m = 0.4\ \mathrm{kg}$

Change in specific internal energy: $u_2 - u_1 = -55\ \mathrm{kJ/kg}$;
no significant change in kinetic/potential energy

**Determine the net heat transfer between the gas and the surrounding**

# Example 2.2 in Moran



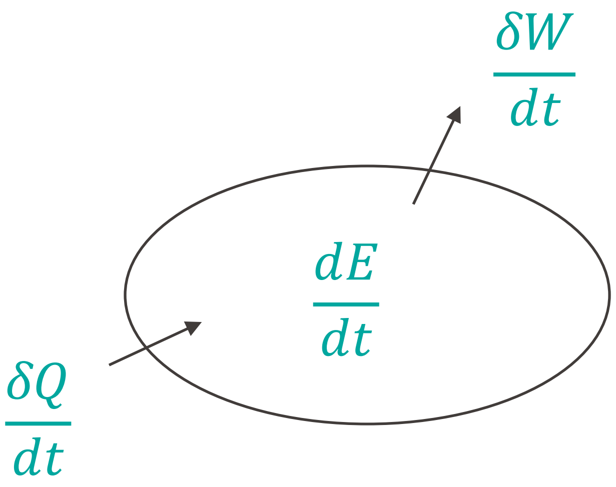

The gas inside the piston-cylinder assembly forms a closed system

$$\Delta E = m(u_2 - u_1) = -22 \text{ [kJ]} \qquad W = \int_{V_1}^{V_2} p dV = \int_{V_1}^{V_2} \frac{p_1 V_1^{1.5}}{V^{1.5}} dV = -\frac{2 p_1 V_1^{1.5}}{V^{0.5}} \Big|_{V_1}^{V_2} = 17.6 \text{ [kJ]}$$

$$\Delta E = Q - W \Rightarrow Q = \Delta E + W = -4.4 \text{ [kJ]}$$

# Time Rate Form of First Law for a Closed System

| | | | | |
|---|---|---|---|---|
| **Time rate of** change in the amount of energy contained within a system at time *t* | = | **Net rate** at which energy is transferred into the system by heat transfer at time *t* | − | **Net rate** at which energy is transferred out of the system by work at time *t* |

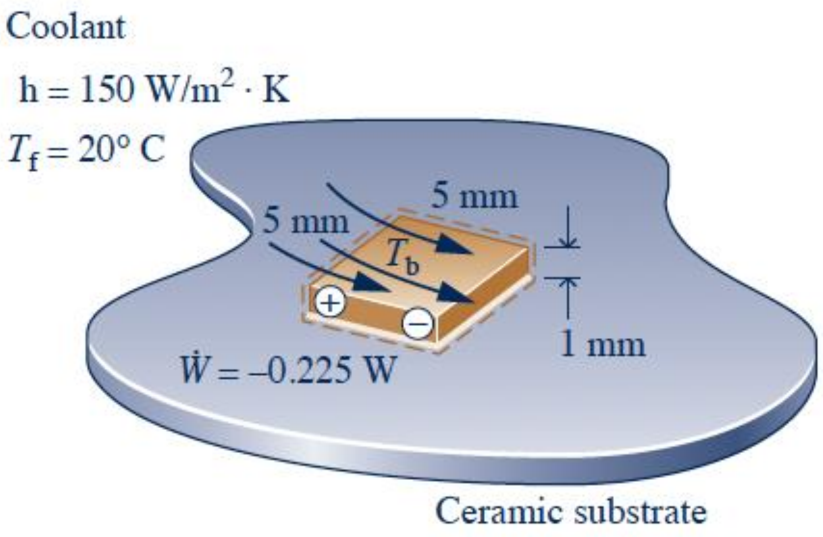



$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

Heat flow rate - Power

Everything here is in [W]

# Example 2.5 in Moran




A silicon chip (5 mm x 5 mm x 1 mm) at a **steady state**

Electric power input is 0.225 W

Only the top surface is exchanging heat with the surrounding

$$\dot{Q}_{cool} = hA(T - T_f)$$

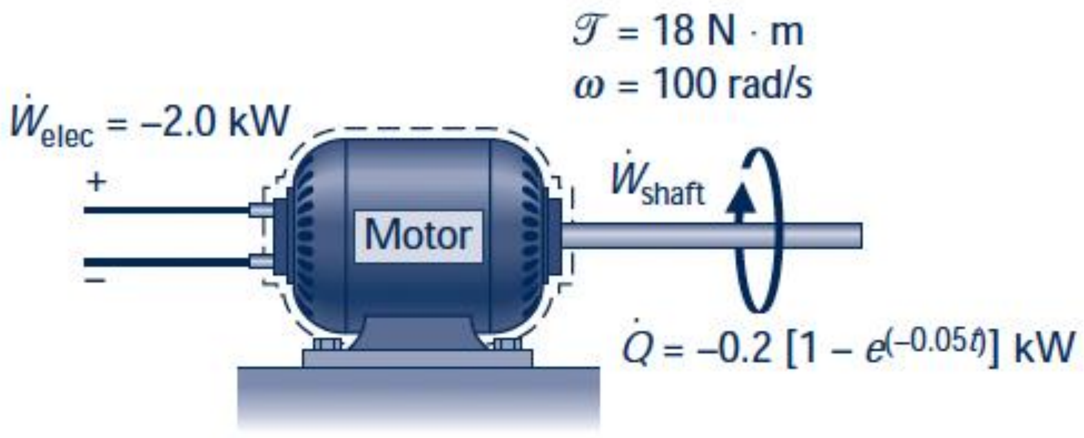
**Determine the surface temperature of the silicon chip**

Our system is the silicon chip

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \Rightarrow 0 = -\dot{Q}_{cool} - \dot{W}$$

$$\dot{Q}_{cool} = hA(T - T_f) \Rightarrow T = \frac{\dot{Q}_{cool}}{hA} + T_f = 80\,°\text{C}$$

# Example 2.6 in Moran




A motor operates with constant electric power input 2 kW, shaft speed $\omega$, and applied torque $\mathcal{T}$

The heat transfer rate between the motor and the ambient follows

$$\dot{Q} = -0.2(1 - e^{-0.05t})$$ $\dot{Q}$ in [kW], $t$ in [s]

**Plot the net heat transfer rate, the net power and the energy change of the motor system as a function of time**

Our system is the motor

$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

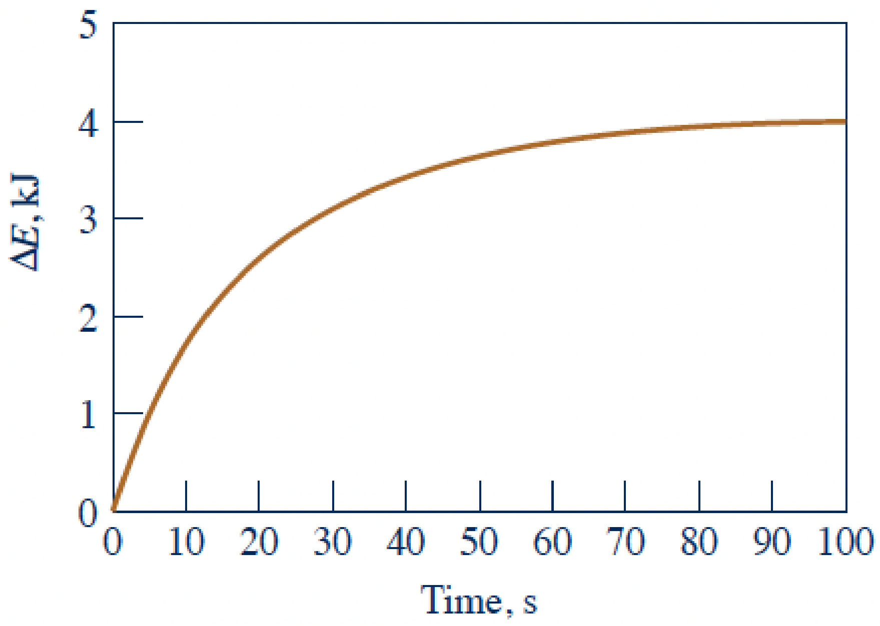
$$\dot{W} = \dot{W}_{elec} + \dot{W}_{shaft} = -2\ [\mathrm{kW}] + \mathcal{T}\omega = -0.2\ [\mathrm{kW}]$$

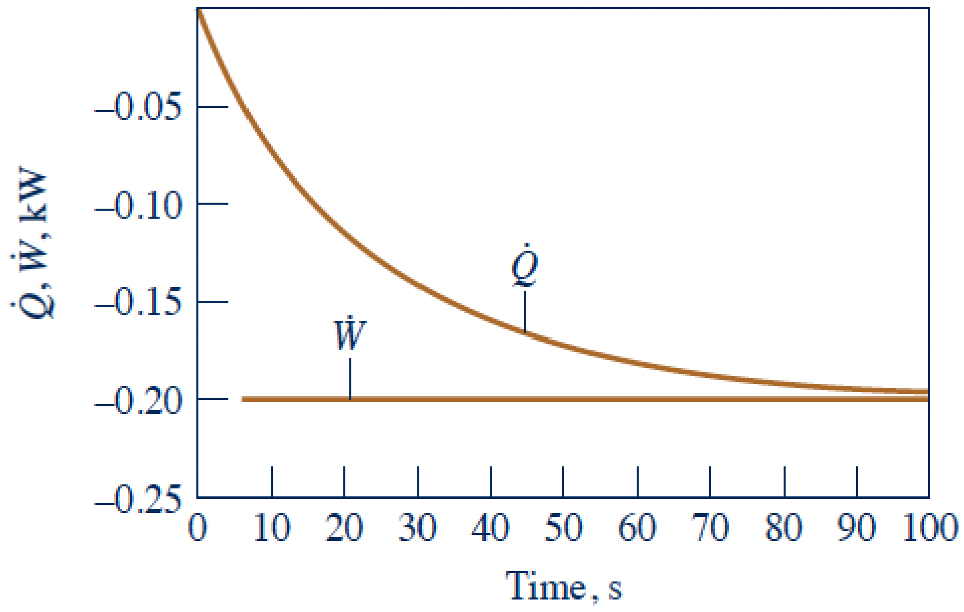
$$\frac{dE}{dt} = \dot{Q} - \dot{W} = -0.2(1 - e^{-0.05t}) + 0.2 = 0.2e^{-0.05t}\ [\mathrm{kW}]$$ $t$ in [s]

$$\Delta E = \int_0^t 0.2e^{-0.05t} = 4(1 - e^{-0.05t})[\mathrm{kJ}]$$ $t$ in [s]

# Example 2.6 in Moran



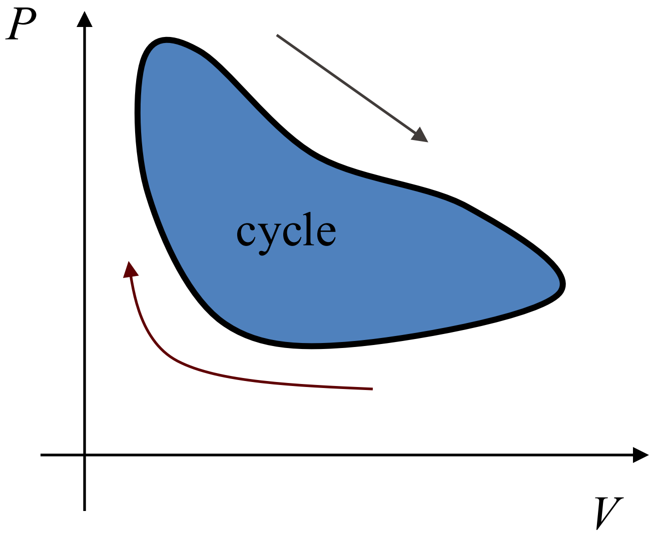



After 100 seconds, we can consider the motor system to be at a steady state

# Thermodynamics Cycles

- A thermodynamic cycle is a sequence of processes that begins and ends at the same state.

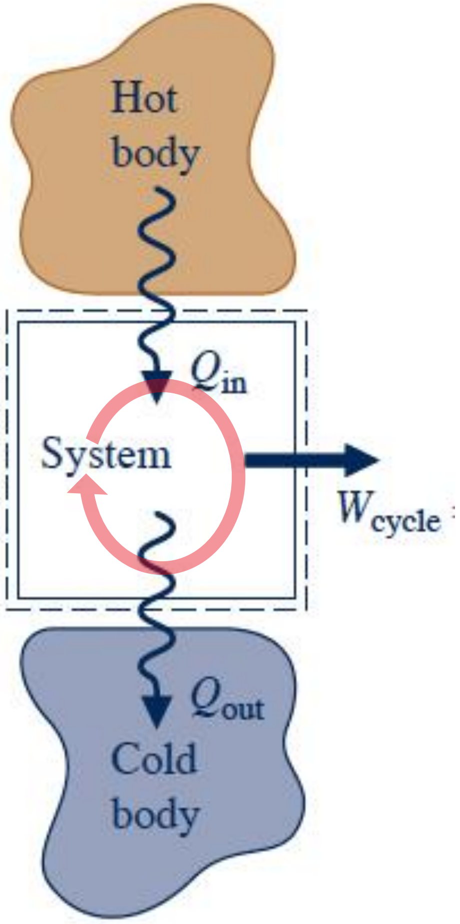



$$\Delta E_{cycle} = Q_{cycle} - W_{cycle}$$

$$\Delta E_{cycle} = 0 \Rightarrow Q_{cycle} = W_{cycle}$$

# Power Cycle






System undergoing a cycle to deliver a net work transfer to their surroundings

$$W_{cycle} = Q_{in} - Q_{out}$$

Thermal efficiency

$$\eta = \frac{W_{cycle}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

First law requires $\eta \leq 1$; we will provide a better bound with the second law of thermodynamics

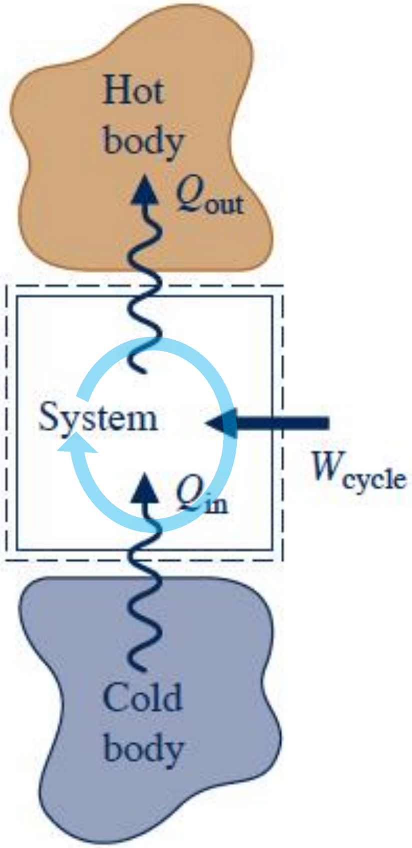
# Typical Thermal Efficiencies

- Nuclear power plant: 0.32-0.34
- Fossil fuel power plant: 0.35-0.48
- Combustion engine: 0.35-0.42 (gasoline/diesel)

This means around 60% of input energy is discharged to the environment.

# Refrigeration and Air Conditioning Cycles

Outdoor at 32 degC




Indoor at 25 degC

System undergoing a cycle to transfer heat from a cold body to a hot body

$$0 = Q_{in} - Q_{out} + W_{cycle}$$

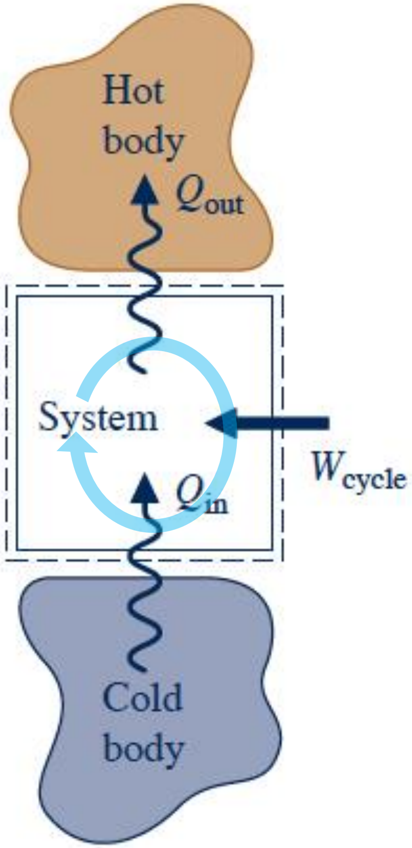
Coefficient of performance (COP) for refrigeration and AC

$$\beta = \frac{Q_{in}}{W_{cycle}} = \frac{Q_{in}}{Q_{out} - Q_{in}}$$

$W_{cycle}$ is typically provided by electricity

# Heat Pump Cycles

Indoor at 20 degC




Outdoor at 0 degC

System undergoing a cycle to transfer heat from a cold body to a hot body

$$0 = Q_{in} - Q_{out} + W_{\text{cycle}}$$

Coefficient of performance (COP) for heat pump

$$\gamma = \frac{Q_{out}}{W_{cycle}} = \frac{Q_{out}}{Q_{out} - Q_{in}}$$

# Pure Substance

- Pure substance: uniform in chemical composition.
  - Pure water is a pure substance
  - Ice-water mixture is also a pure substance
  - Air can also be treated as pure substance (made of different gas species, but chemical composition has no spatial variation)
  - Aerosol is NOT a pure substance

The chemical composition of the small suspended particles are not the same as the air

# Phase

- Homogeneous in both chemical composition and physical structure (solid, liquid, vapor/gas)

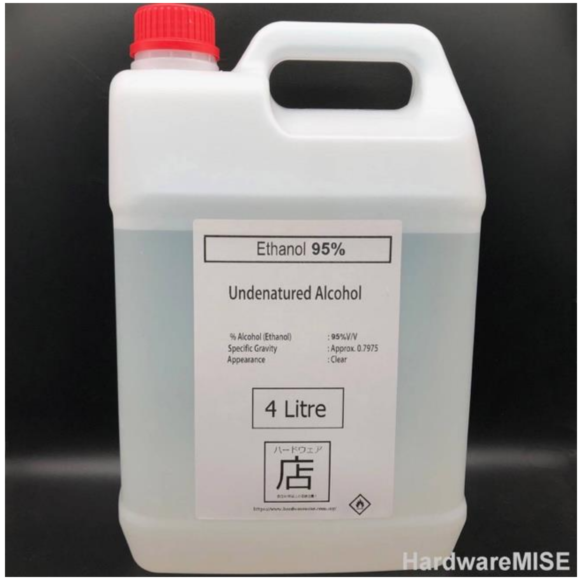
**Ice-water mixture**

Two phases

**Water-oil mixture**

Two phases

**Ethanol diluted with water**

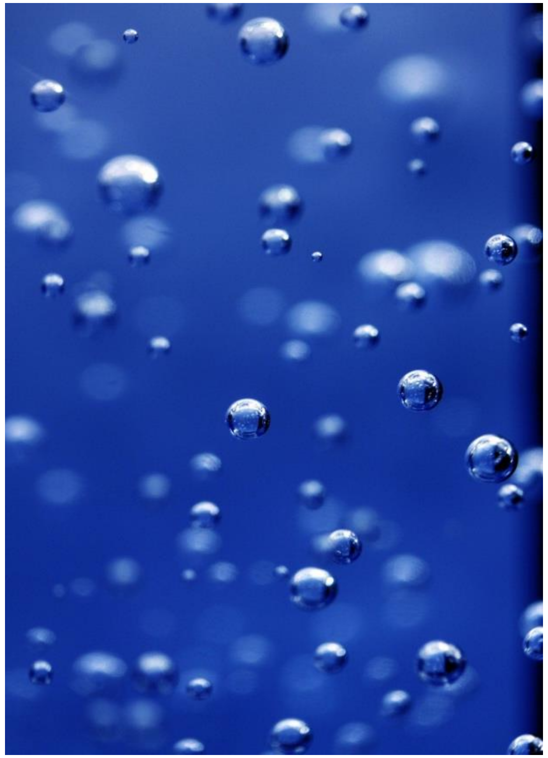



Single phase

# Pop Quiz



System: salt (NaCl) solution + $CO_2$ bubbles



**How many phases are there?**

A. 1
B. 2
C. 3
D. 4

Scan the QR code with your device
Or go to **echo360poll.eu**

Enter Code

**luepfl**

# Intensive Thermodynamic Properties

- Pressure
- Temperature
- Density
- Specific volume
- Specific internal energy
- …

These intensive properties are not all independent in a system

# How to Describe a System's Intensive State

- **State principle**: for closed systems

| |
|---|
| # of independent properties = # of relevant work exchange modes + 1 (associated with heat) |

  - E.g., for gas in a piston-cylinder assembly, number of independent properties: 2 (**temperature** associated with heat transfer and **pressure** associated with compression/expansion work)

- **Simple system**: only one work exchange mode as the system undergoes quasiequilibrium processes (**two independent properties**).

# Pure Substance p-v-T Relation

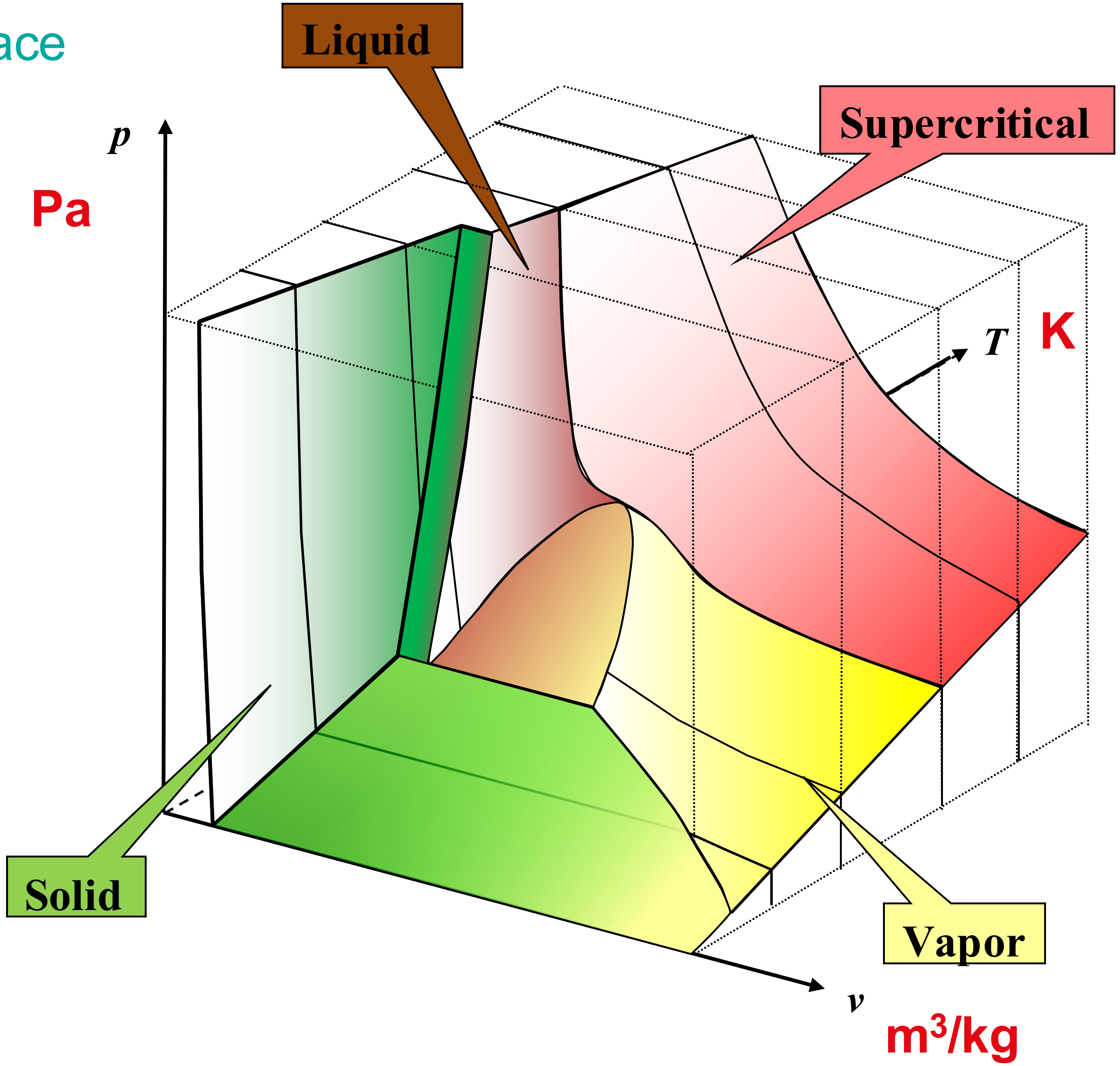
## Two independent variable: a surface

Single phase regions:

- **Solid**
- **Liquid**
- **Vapor**
- **Supercritical**

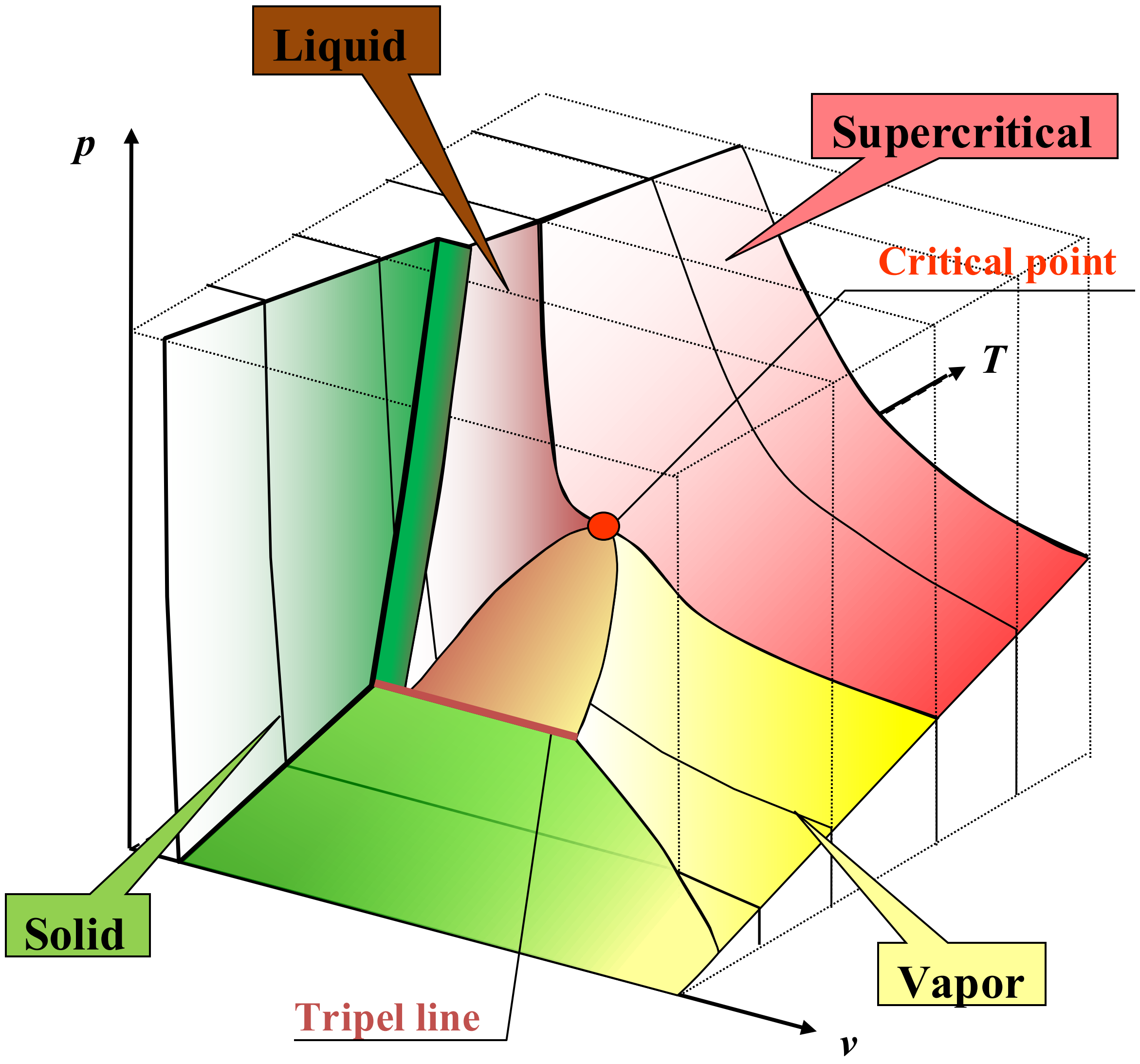
Two phase regions exist between the single-phase regions (co-existence of two phases in equilibrium)

- **Solid-vapor**
- **Liquid-vapor**
- **Solid-liquid**



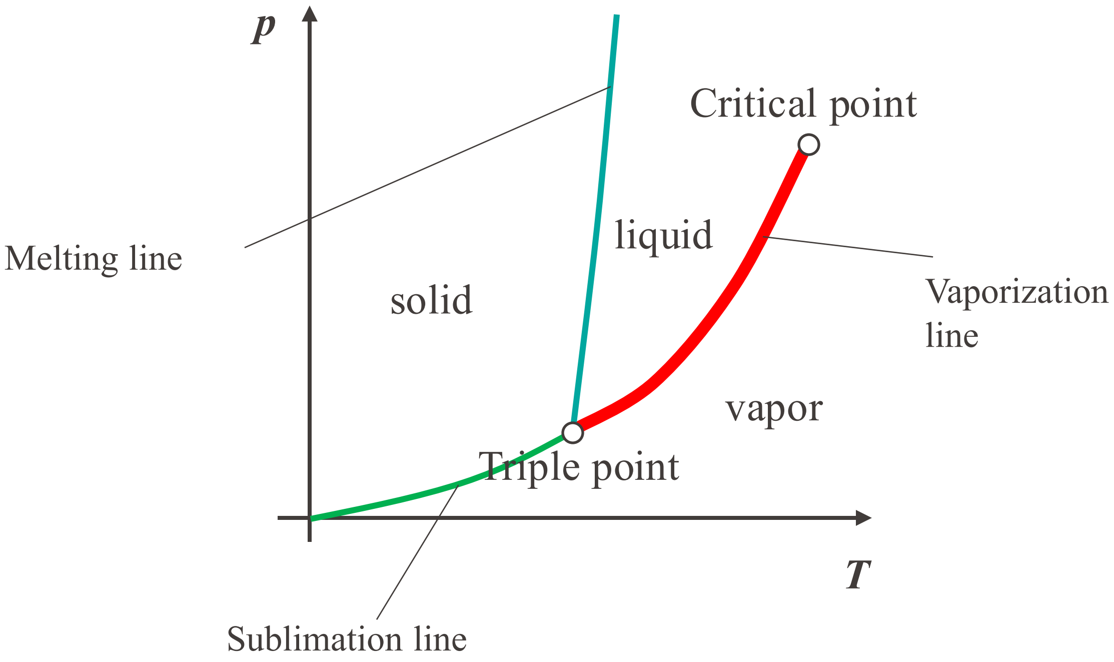
# Pure Substance p-v-T Relation

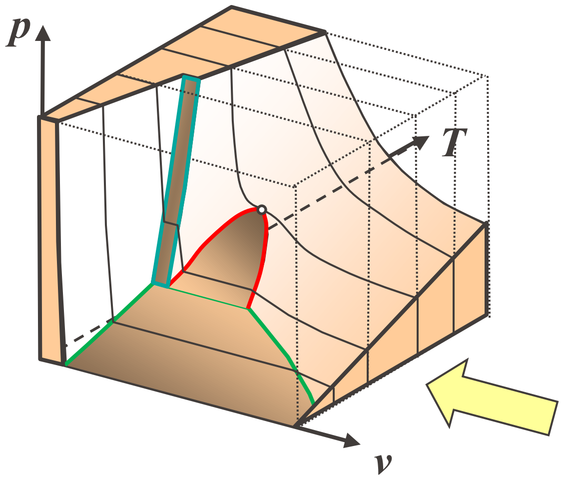
- In two-phase regions *p* and *T* are not independent! Need *v* to determine state.
- State where phase change begins or ends is called ***saturation state***.
- Meeting point of the saturated liquid and saturated vapor lines is called ***critical point***. Maximum *p* and *T* at which liquid and vapor can co-exist.
- ***Triple line*** separates liquid-vapor and solid-vapor two-phase regions. Three phases co-exist along it.



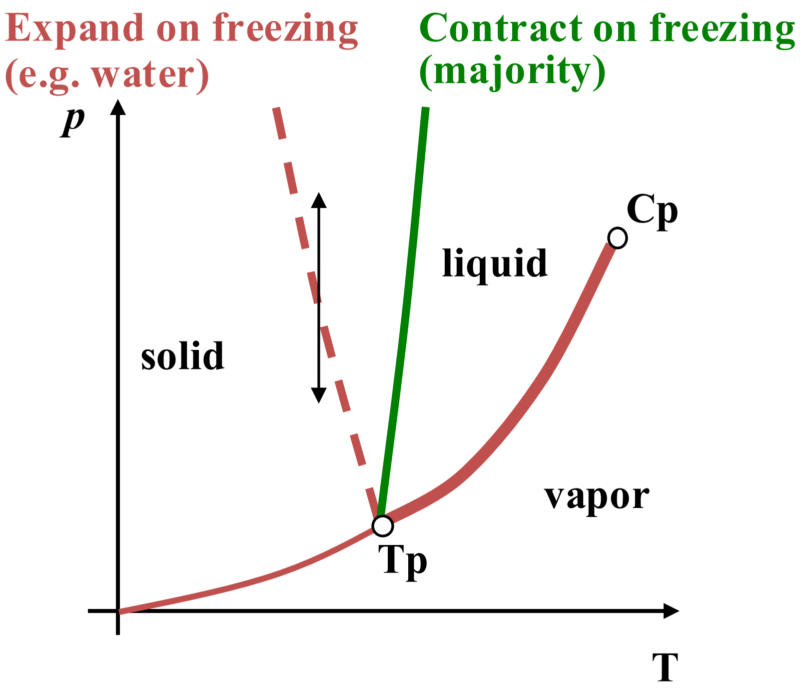
# Phase Diagram

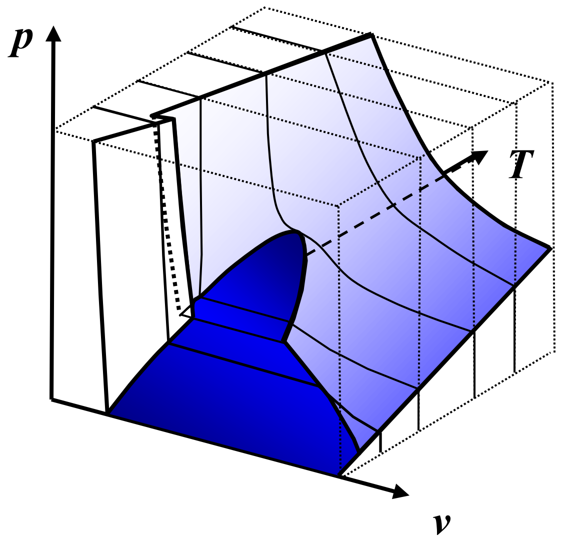
- Projection to p-T plane

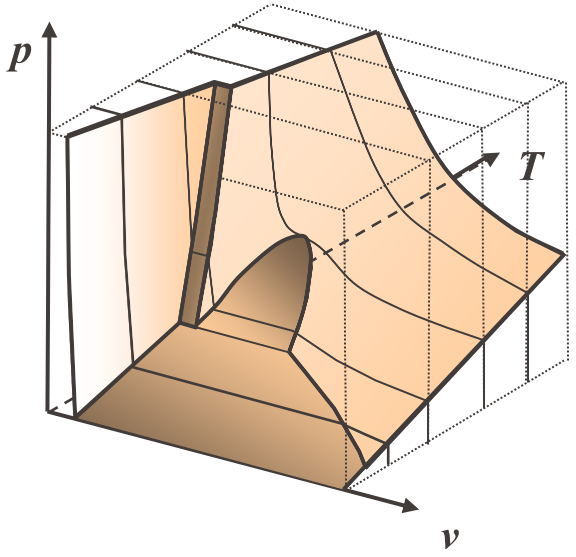


# p-T diagram

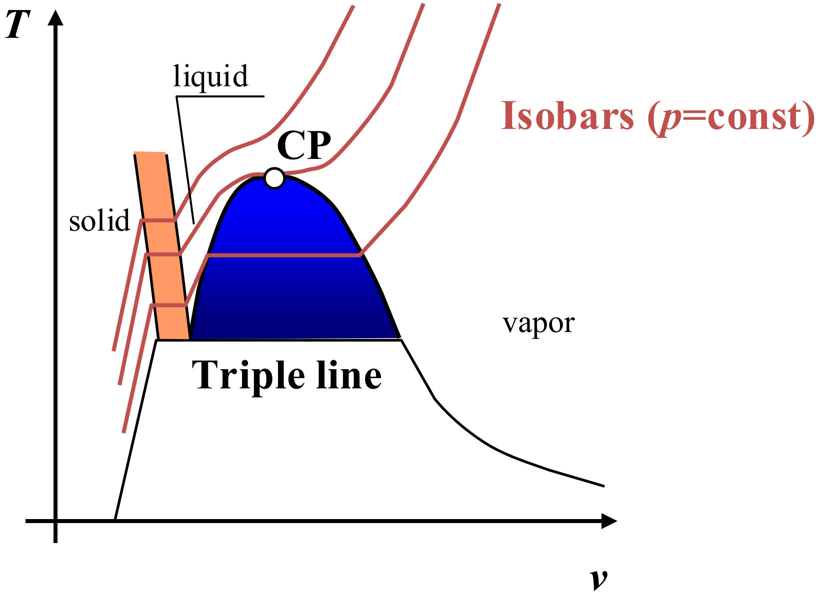

Expand on freezing
(e.g. water)
Contract on freezing
(majority)
p
solid
liquid
Cp
vapor
Tp
T

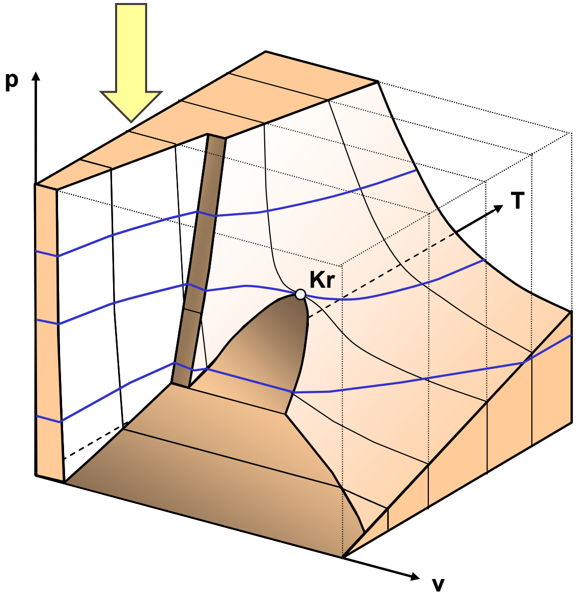

p
T
v


p
T
v

# Phase Diagram

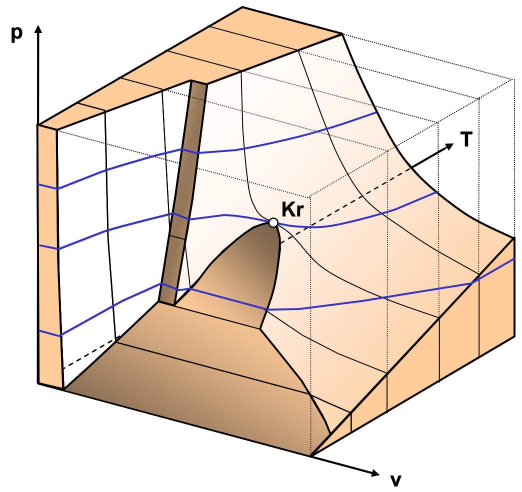
- Projection to T-v plane



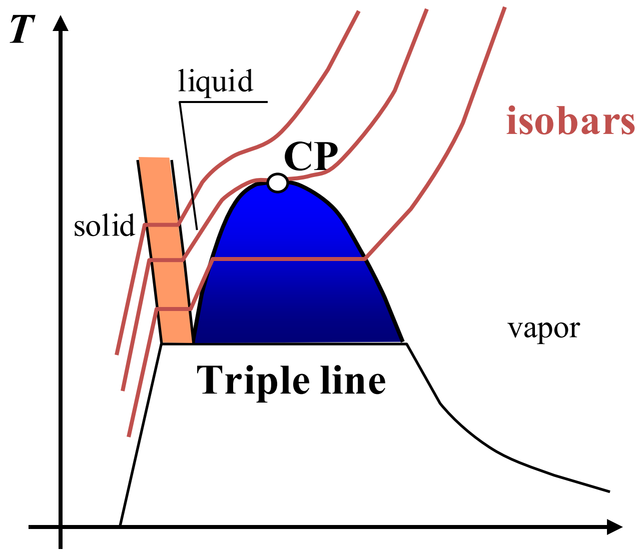



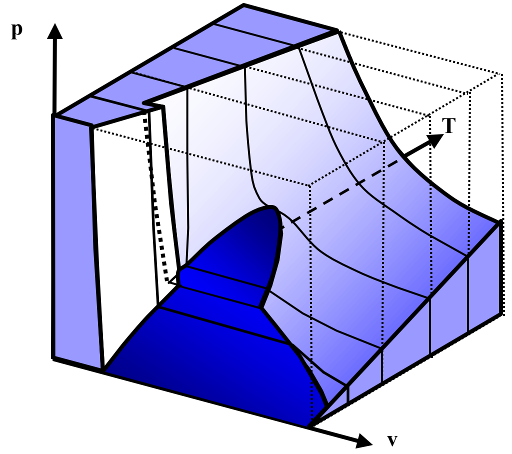

- At very low pressures: phase change from solid to vapor directly
- At moderate pressure (below critical pressure): solid to liquid, and then to vapor. Temperature is constant during isobaric phase change.
- For high pressures, no distinct phase transition between liquid and vapor

# T-v Diagram

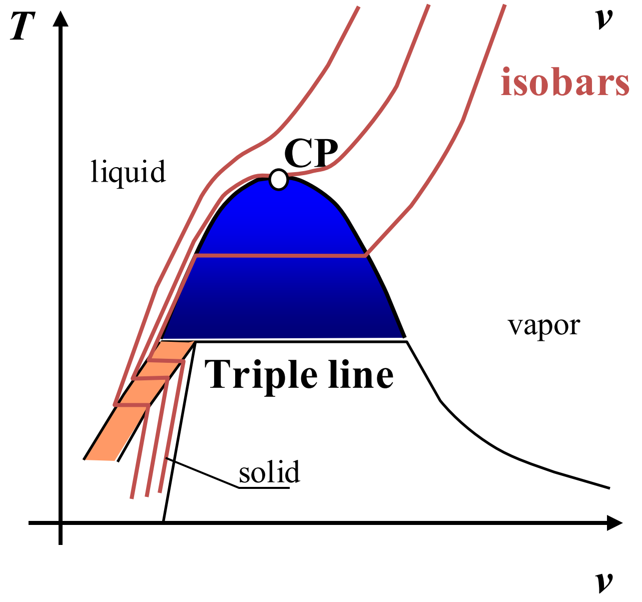



**Contract on freezing**

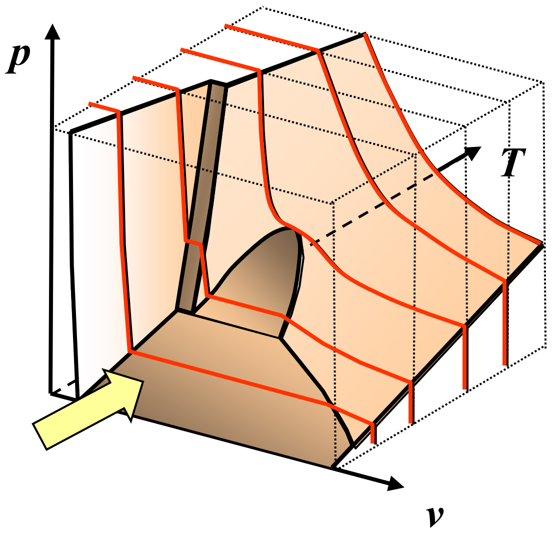


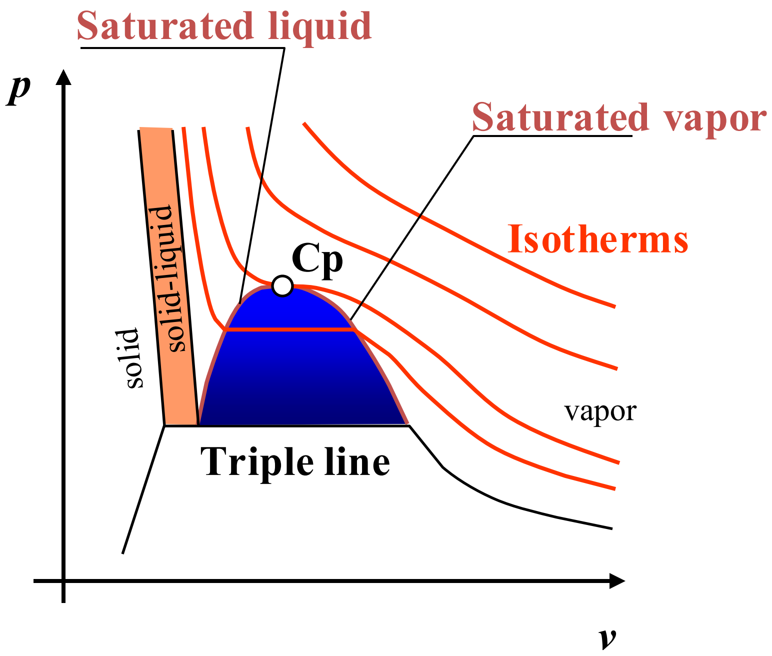




**Expand on freezing**



# p-v Diagram




- At low temperatures, phase change from solid to vapor directly
- At moderate temperatures (below CP): solid to liquid, and then to vapor. Pressure is constant during isobaric phase change (between saturated liquid and saturated vapor)
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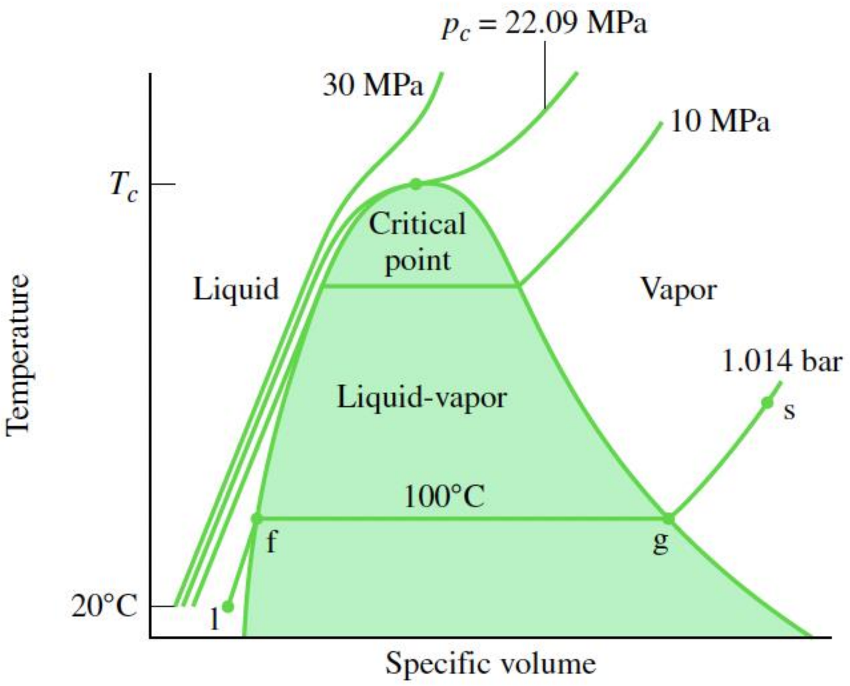
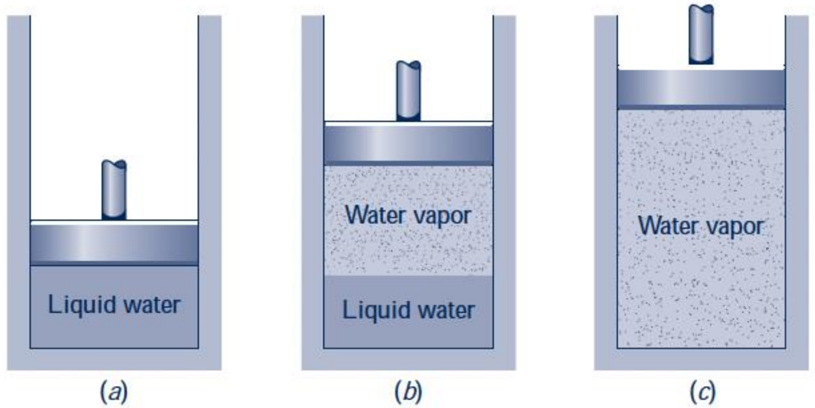
# Two-Phase Liquid-Vapor Mixture




Quality: $x = \frac{m_{vapor}}{m_{liquid}+m_{vapor}}$

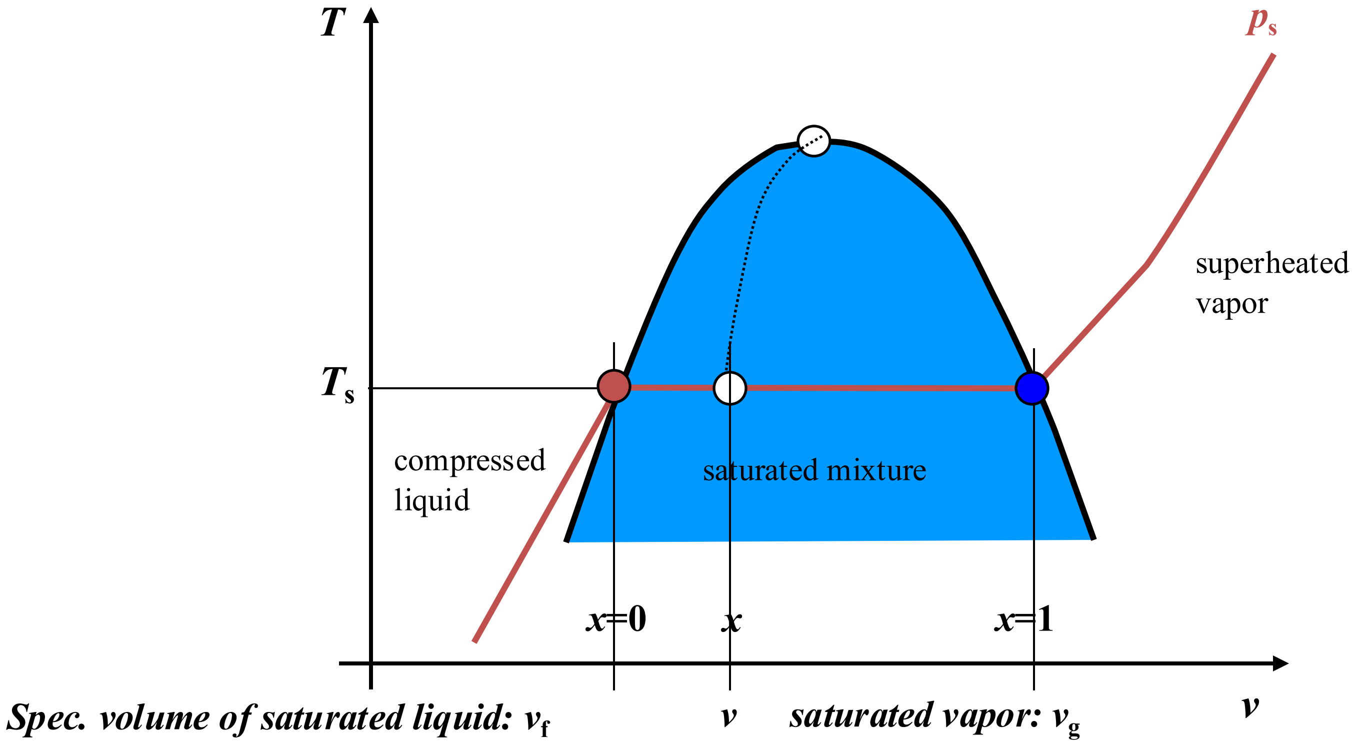
$x = 0$, saturated liquid; $x = 1$, saturated vapor

# Quality

Saturation temperature is only defined after specifying pressure water: 99.97 °C at 1.014 bar

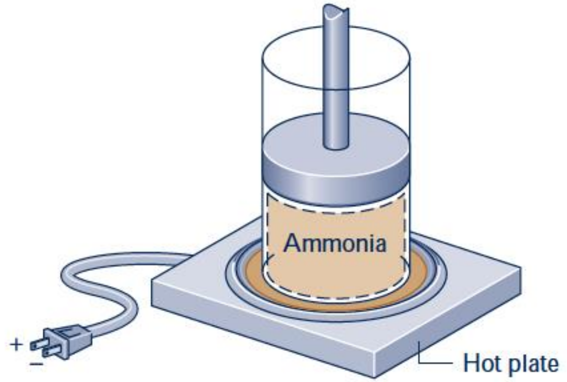
Quality helps us characterize state in two-phase region:

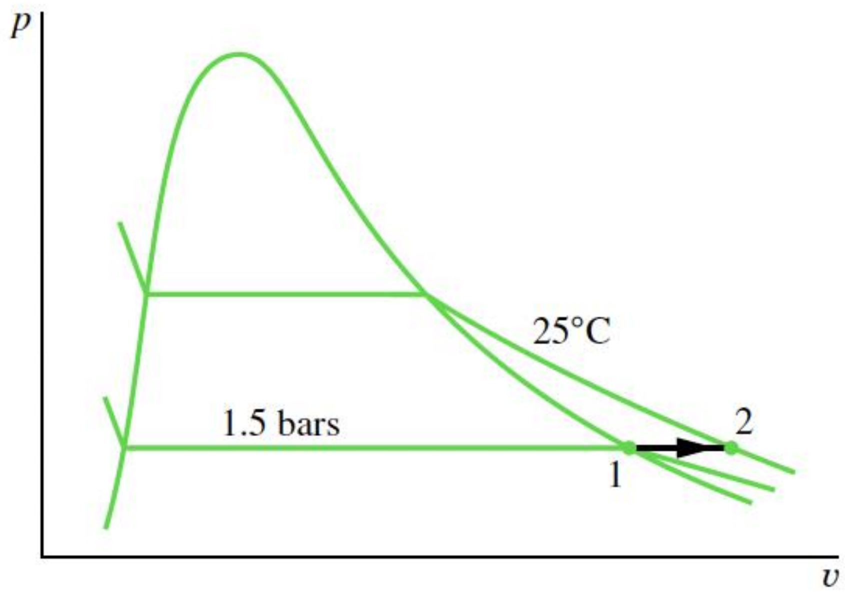
$$y = y_f + x(y_g - y_f)$$



# Example 3.1 in Moran

- A vertical piston-cylinder assembly contains ammonia, initially a saturated vapor, and is placed on a hot plate. The pressure of the ammonia is **1.5 bar**.
- Heating occurs slowly and the ammonia expands at constant pressure until the final temperature is **25°C**.
- **Show the initial and final state in *p*-v- and *T*-*v*-diagrams**



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