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

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EPFL Mechanical Engineering

2025 Fall Semester

Photo Credit: Trougnouf

Exercise Room Situation

	Capacity	# of last week's participants
AAC137	80	16
SG 0 211	112	50
SG 0 213	80	71

Last Time

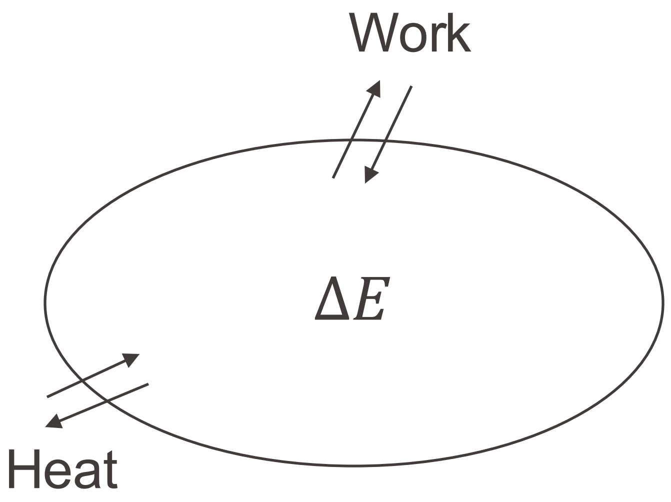
- Explain key concepts in the first law of thermodynamics
    - Energy change
    - Work
    - Heat

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)



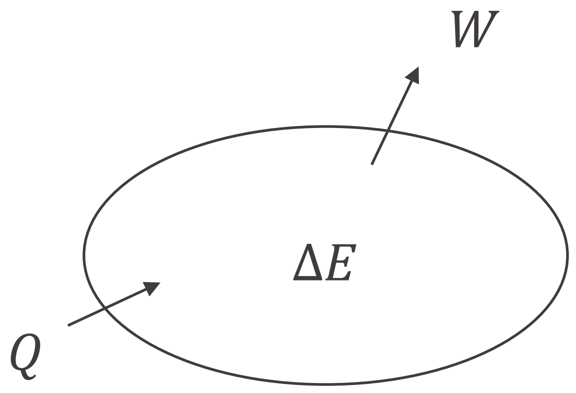
Can be intuitively understood as energy conservation

Energy change = Energy going in – Energy going out

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

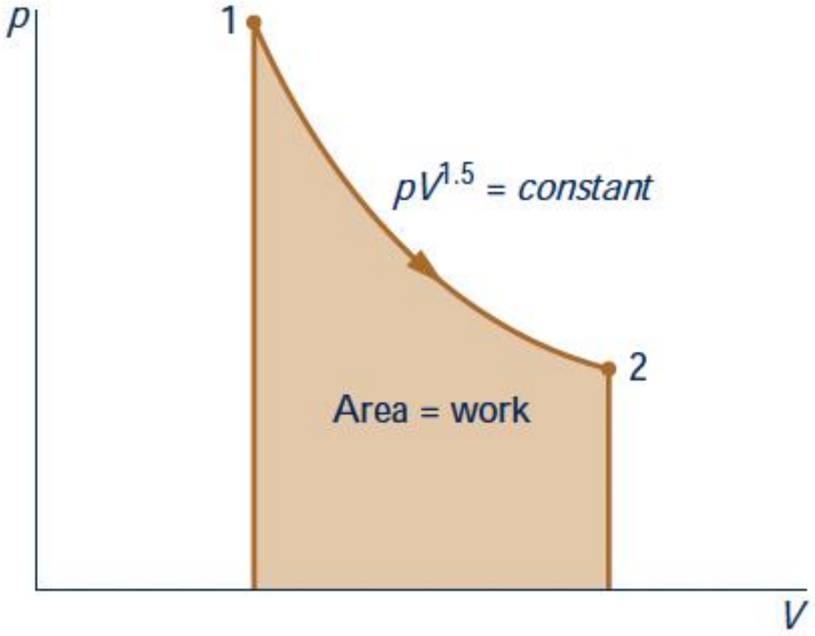
First Law of Thermodynamics for a Closed System

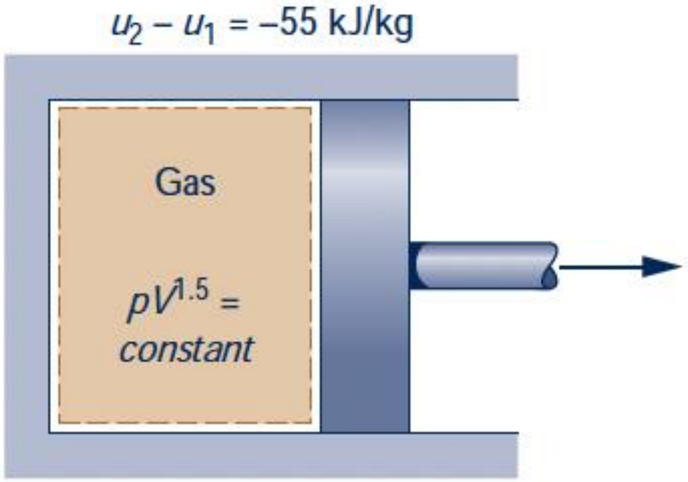
Change in the amount of energy contained within a system during some time interval	=	Net amount of energy transferred **into** the system by heat transfer during the time interval	−	Net amount of energy transferred **out of** the system by work during the time interval



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

Example 2.2 in Moran



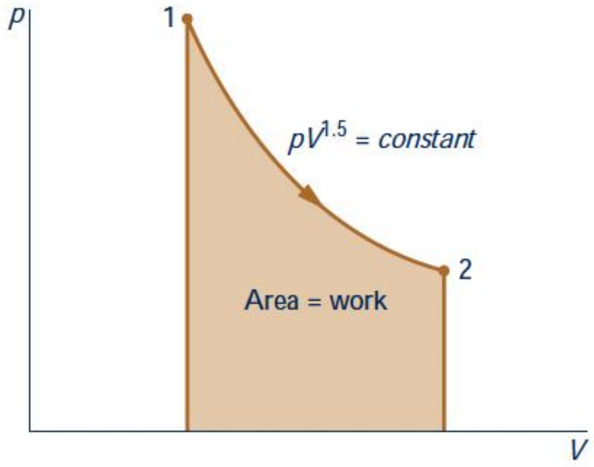


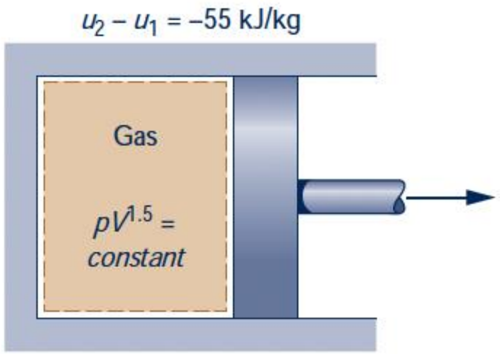
Gas expansion: $V_1 = 0.1\ \mathrm{m}^3$, $p_1 = 3\ \mathrm{bar}$; $V_2 = 0.2\ \mathrm{m}^3$; $pV^{1.5} = \mathrm{const}$, $m = 0.4\ \mathrm{kg}$

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

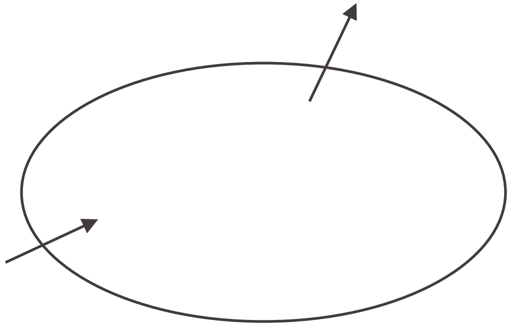
Example 2.2 in Moran



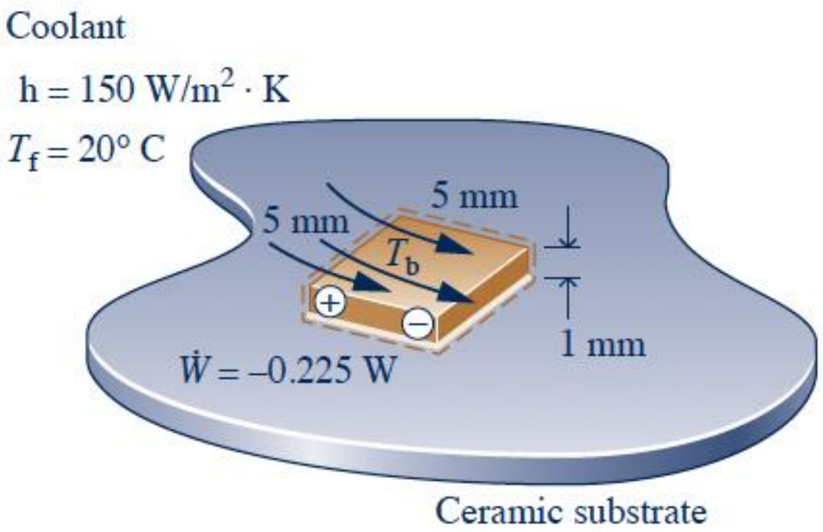


Time Rate Form of First Law for a Closed System

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*



Example 2.5 in Moran



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

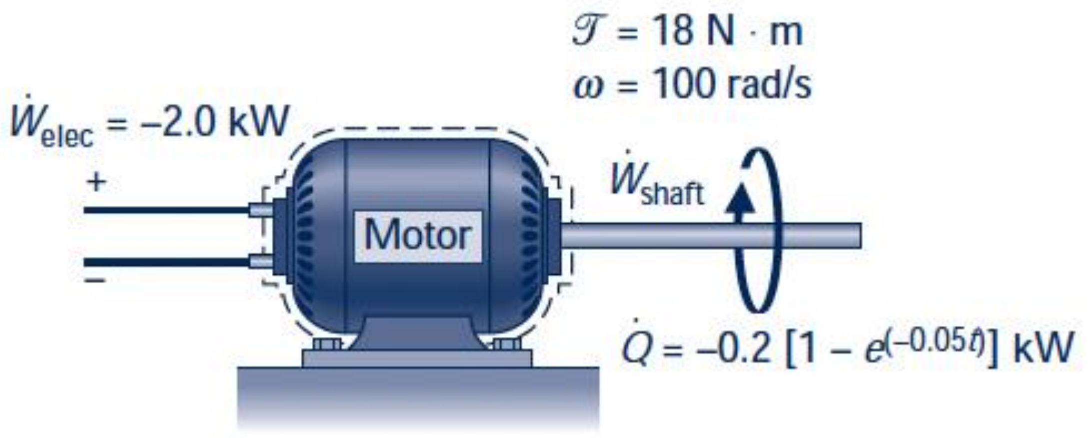
Electric power input is 0.225 W

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

Example 2.6 in Moran



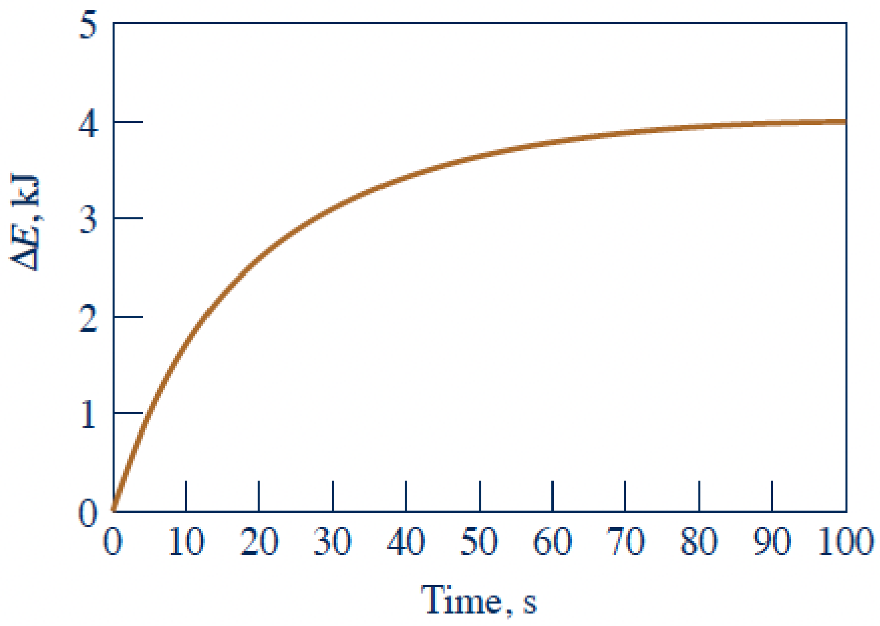
A motor operates with constant electric power input 2 kW, shaft speed ω, and applied torque $\mathcal{T}$

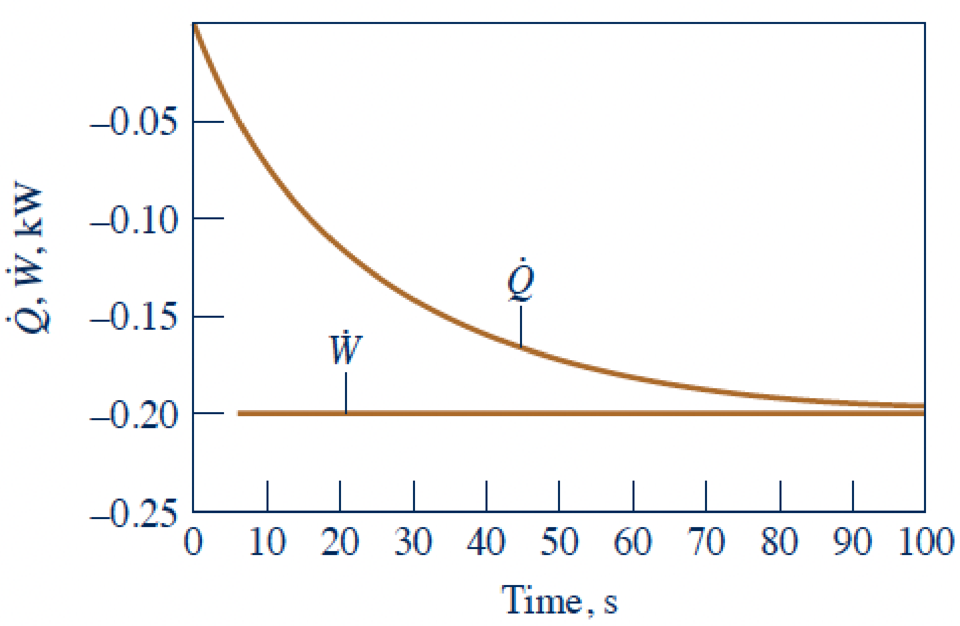
The heat transfer rate between the motor and the ambient follows

$$\dot{Q} = -0.2(1 - e^{-0.05t})$$ $\dot{Q}$ 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

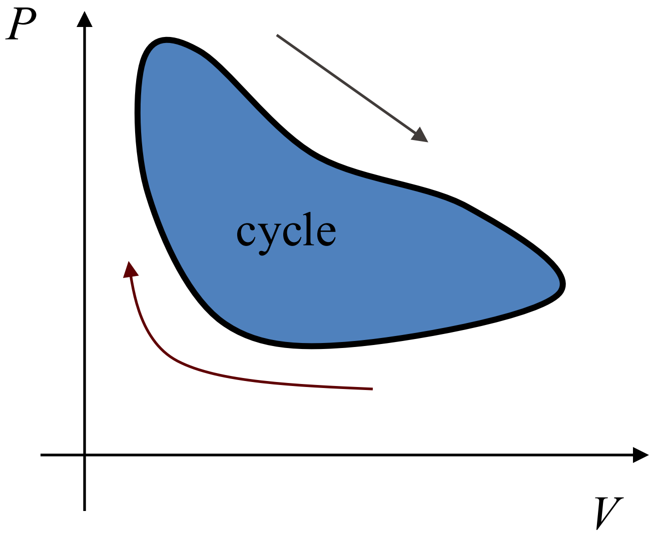
Example 2.6 in Moran



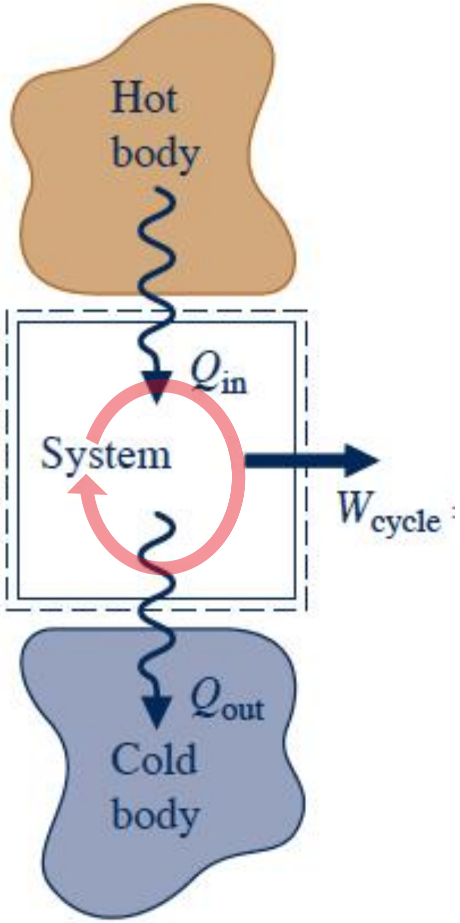


Thermodynamics
Cycles

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



Power Cycle

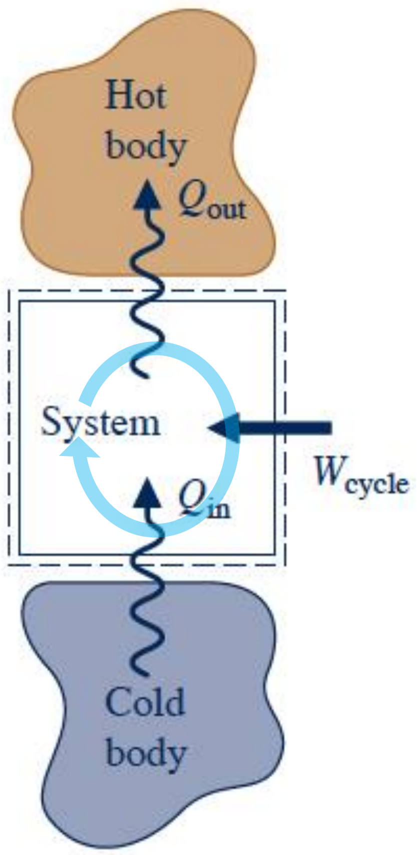


System undergoing a cycle to deliver a net work transfer to their surroundings

Typical Thermal Efficiencies

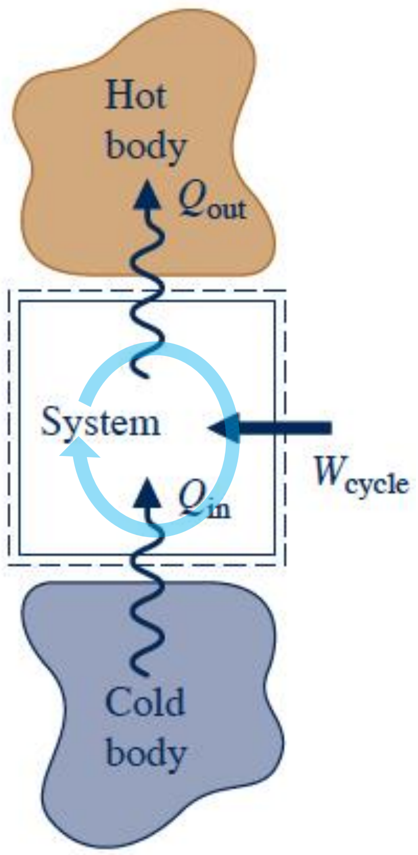
- Nuclear power plant: 0.32-0.34
- Fossil fuel power plant: 0.35-0.48
- Combustion engine: 0.35-0.42 (gasoline/diesel)

Refrigeration and Air Conditioning Cycles



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

Heat Pump Cycles



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

Pure Substance

- Pure substance: uniform in chemical composition.
  - Pure water?
  - Ice-water mixture?
  - Air?
  - Aerosol?

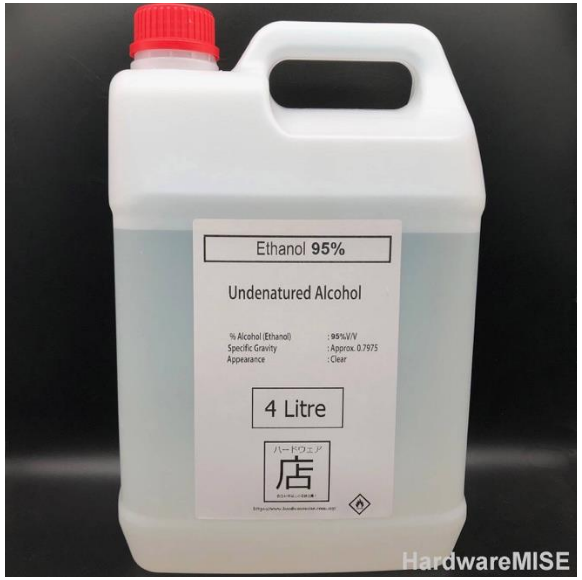
Phase

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

Ice-water mixture

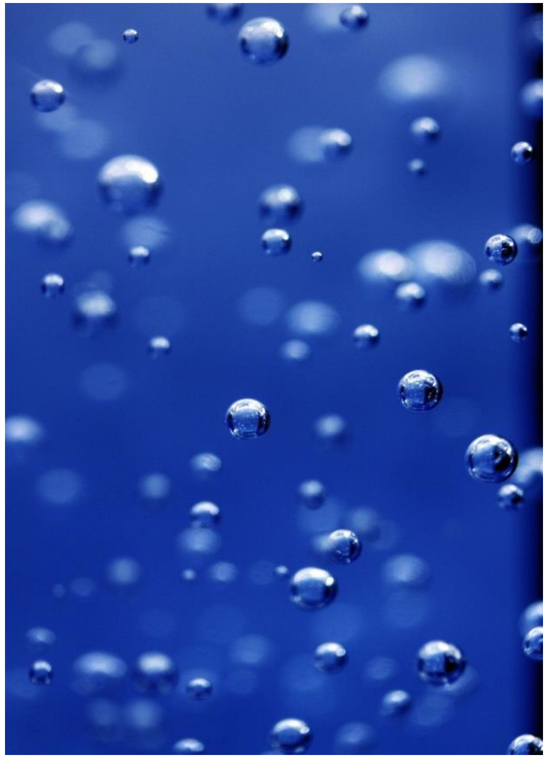
Water-oil mixture

Ethanol diluted with water



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
- …

How to Describe a System's Intensive State

- **State principle**: for closed systems

# of independent properties = # of relevant work exchange modes + 1

  - 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**).

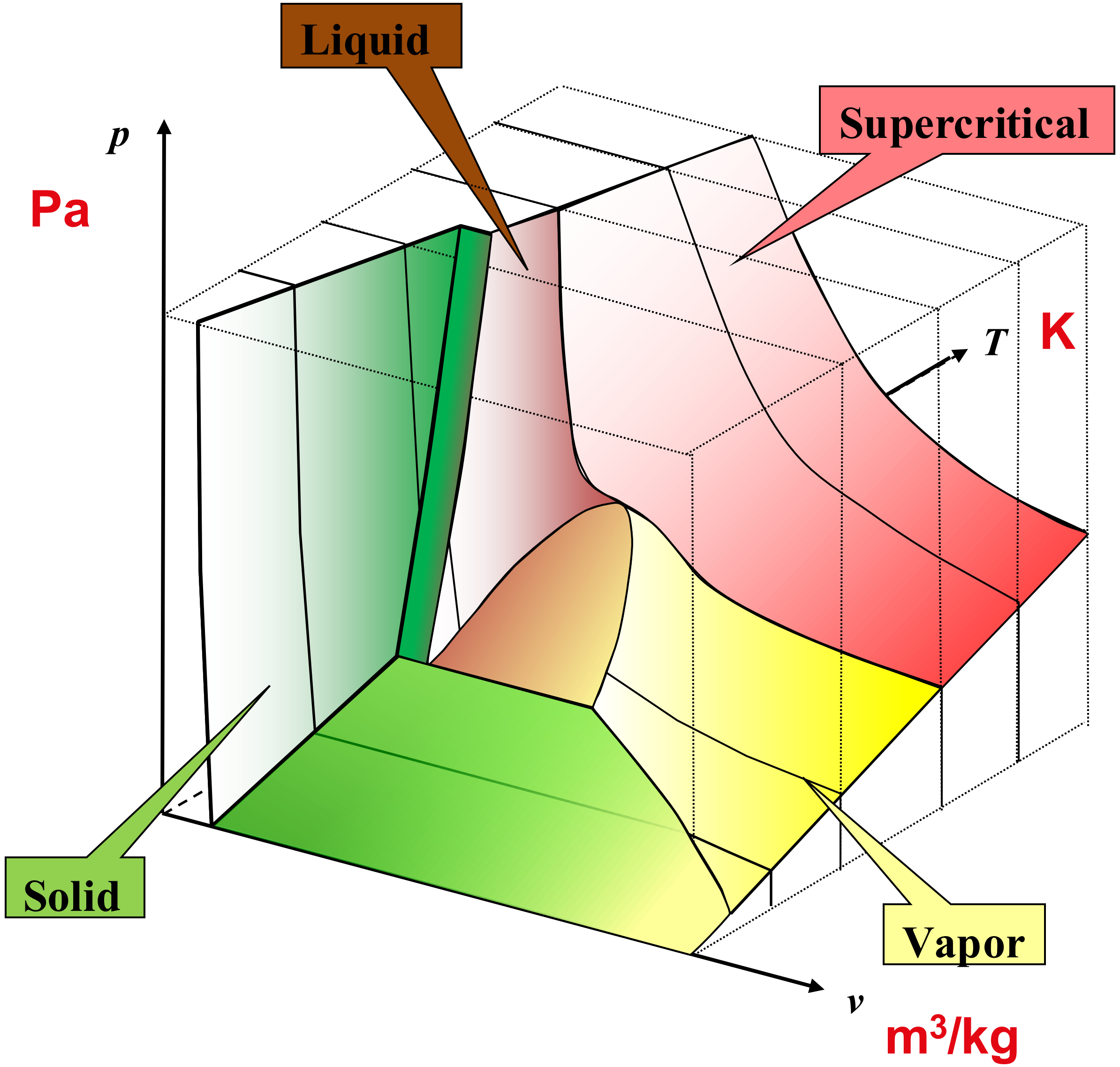
Pure Substance p-v-T Relation

Single phase regions:

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

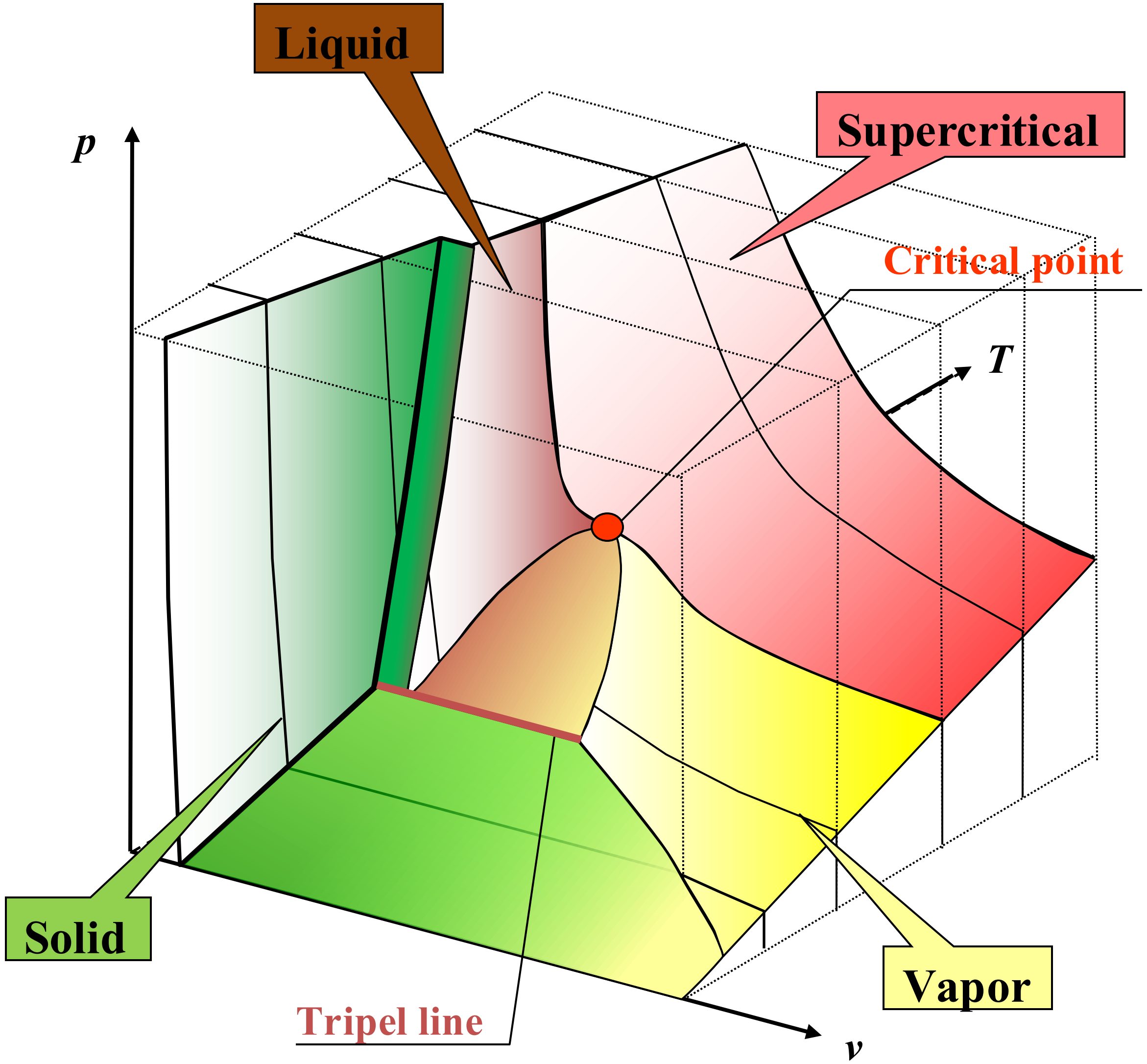
Two phase regions exist between the single-phase regions (co-existence of two phases in equilibrium)

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



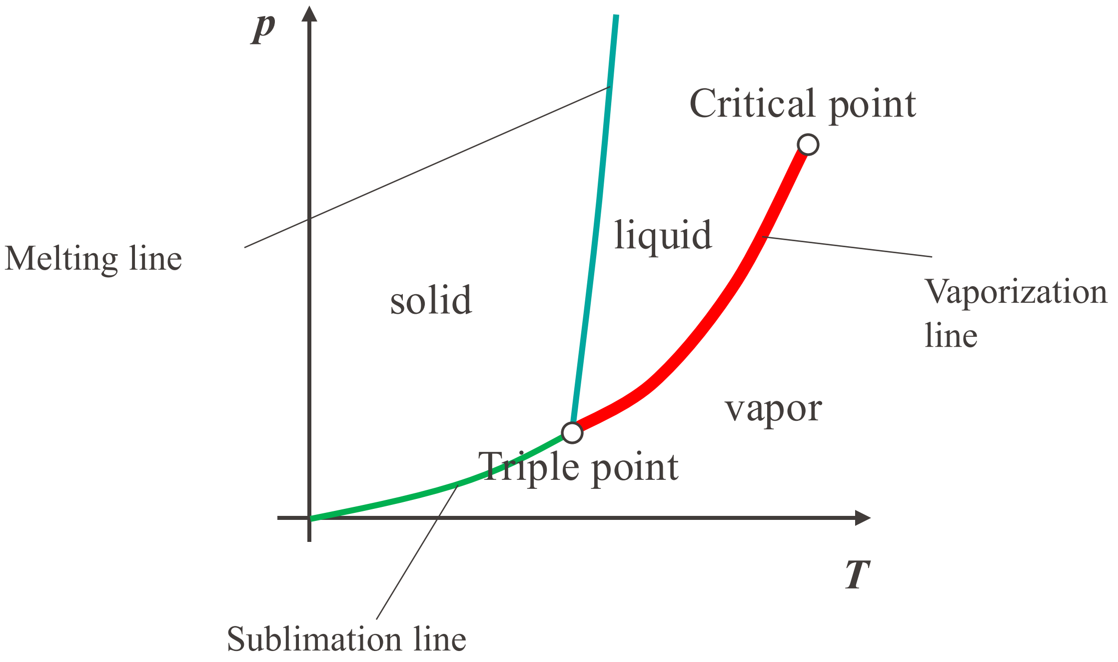
Pure Substance p-v-T Relation

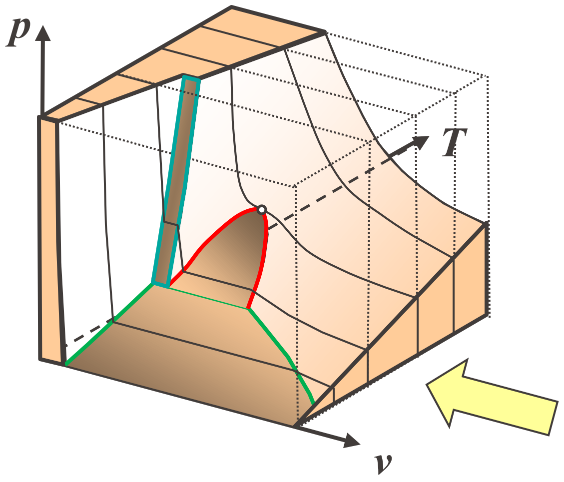
- In two-phase regions *p* and *T* are not independent! Need *v* to determine state.
- State where phase change begins or ends is called ***saturation state***.
- Meeting point of the saturated liquid and saturated vapor lines is called ***critical point***. Maximum *p* and *T* at which liquid and vapor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



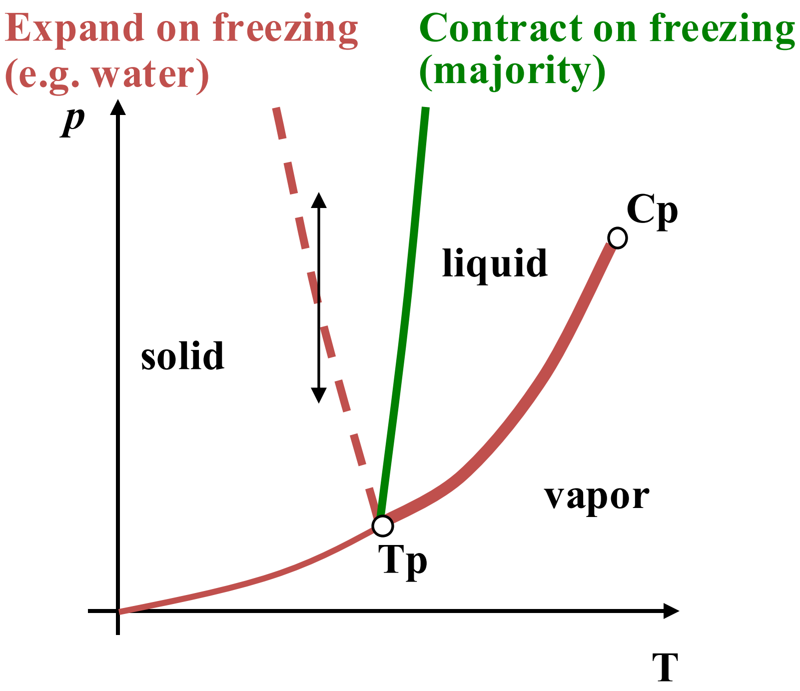
Phase Diagram

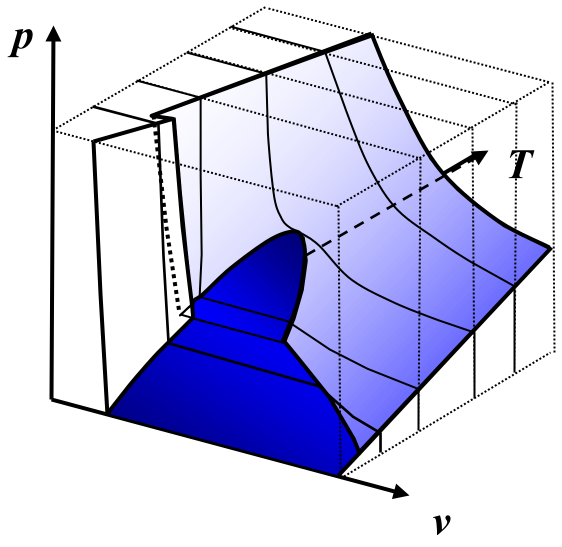
- Projection to p-T plane

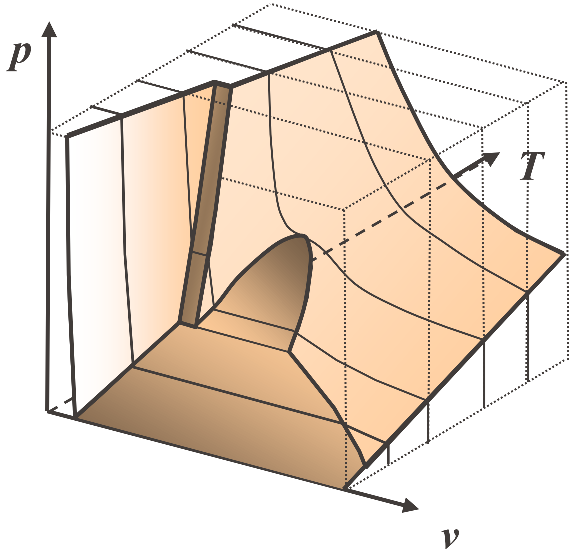




p-T diagram

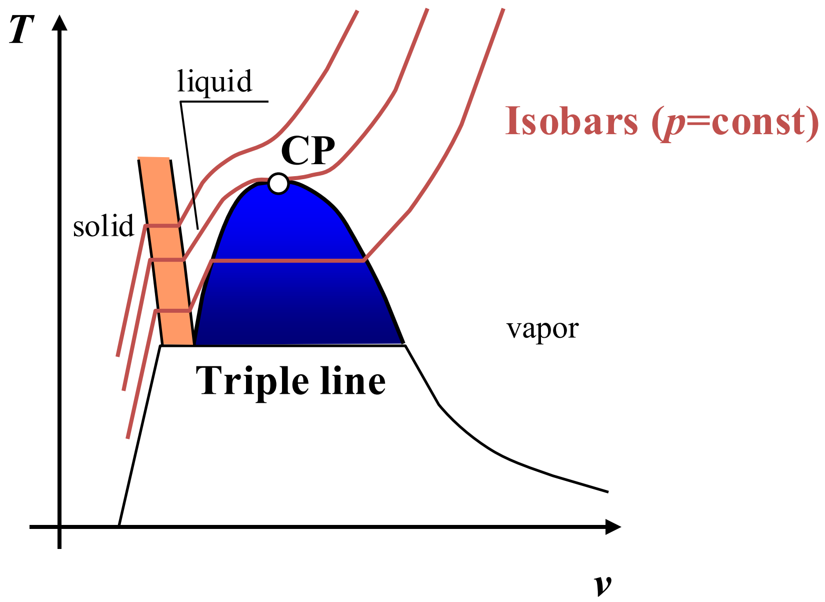

Expand on freezing
(e.g. water)
Contract on freezing
(majority)
p
Cp
liquid
solid
vapor
Tp
T

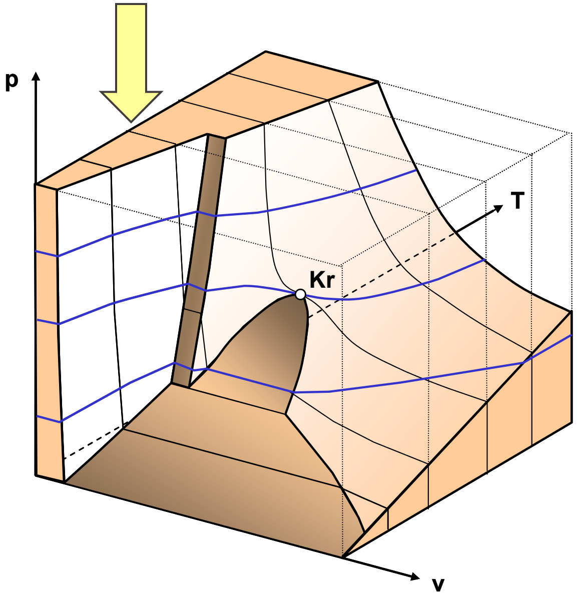

p
T
v


p
T
v

Phase Diagram

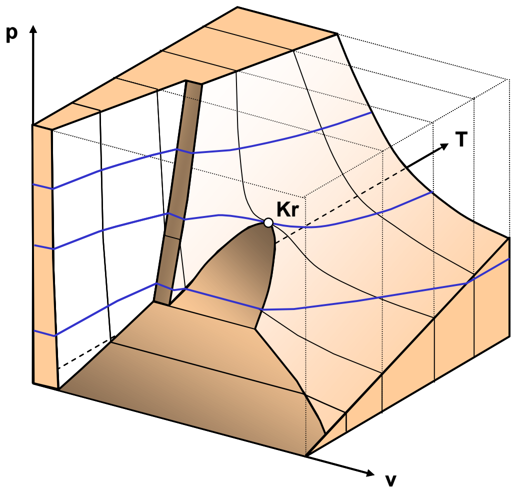
- Projection to T-v plane



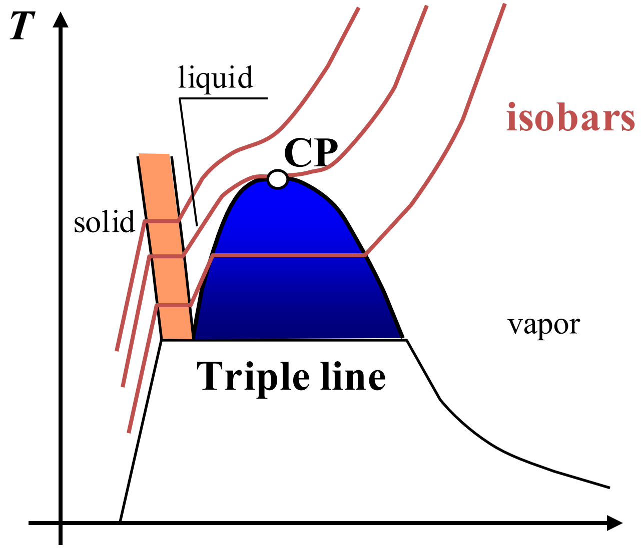


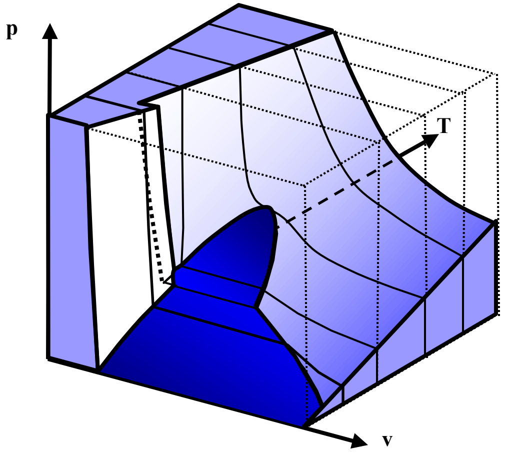
- At very low pressures: phase change from solid to vapor directly
- At moderate pressure (below critical pressure): solid to liquid, and then to vapor. Temperature is constant during isobaric phase change.
- For high pressures, no distinct phase transition between liquid and vapor

T-v Diagram

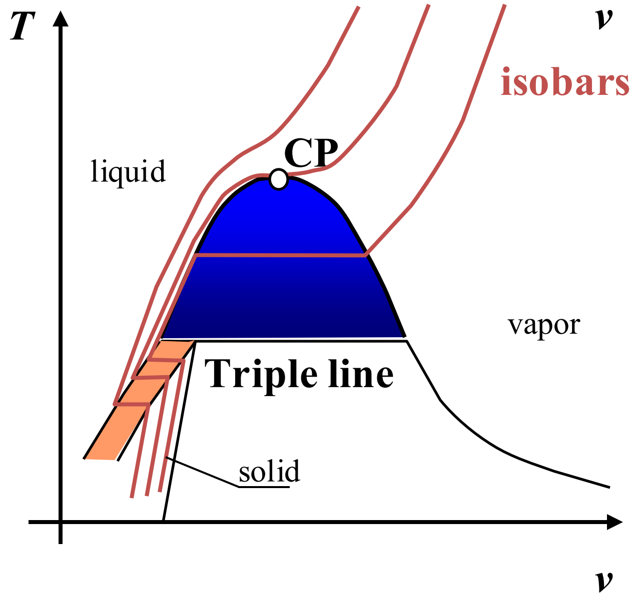


Contract on freezing

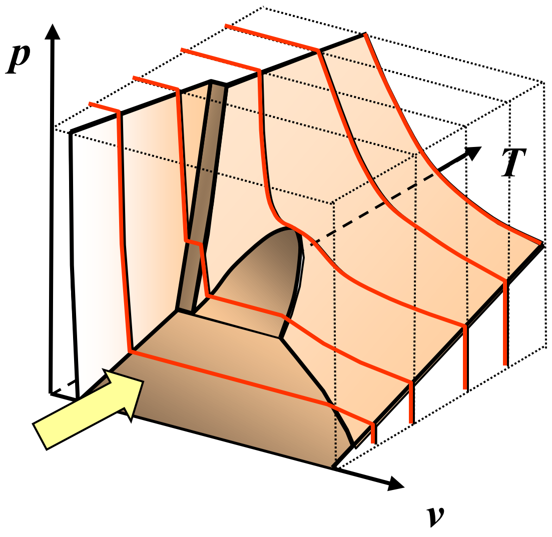


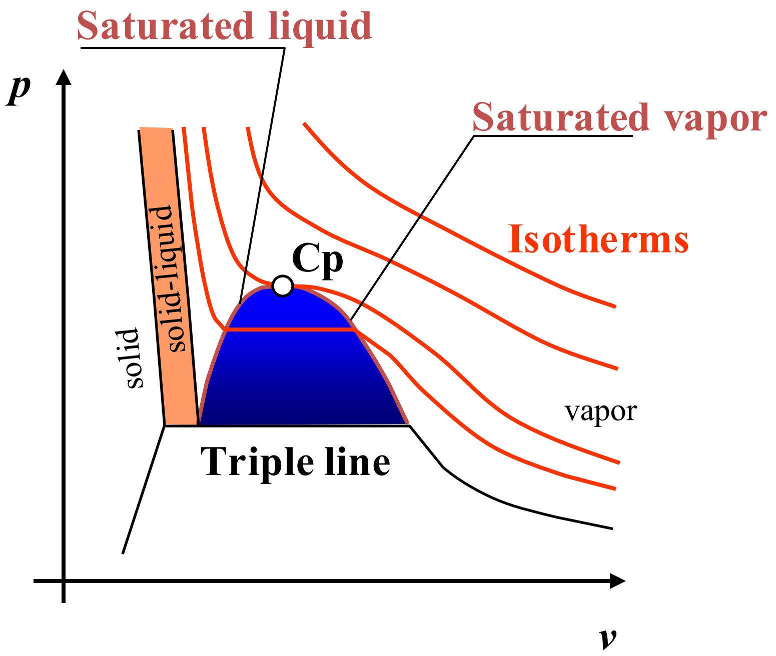


Expand on freezing



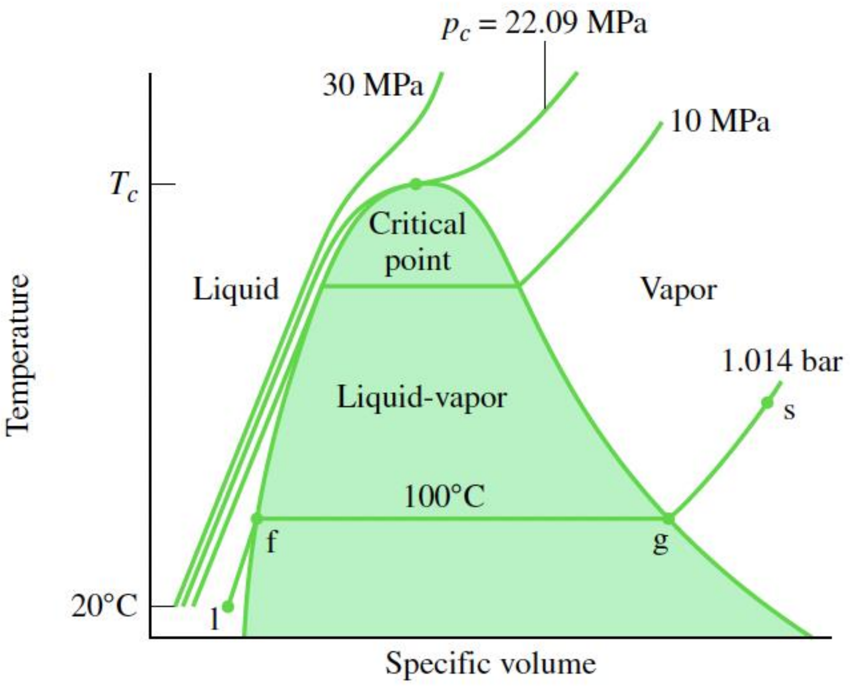
p-v Diagram

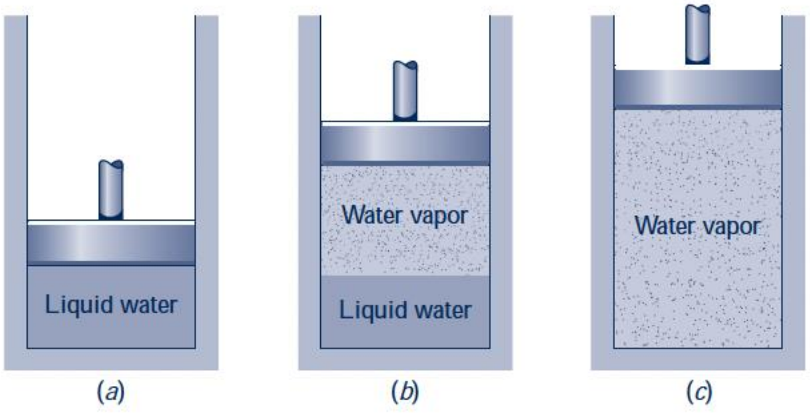




- At low temperatures, phase change from solid to vapor directly
- At moderate temperatures (below CP): solid to liquid, and then to vapor. Pressure is constant during isobaric phase change (between saturated liquid and saturated vapor)
- At high temperatures, no distinct transition between liquid and vapor

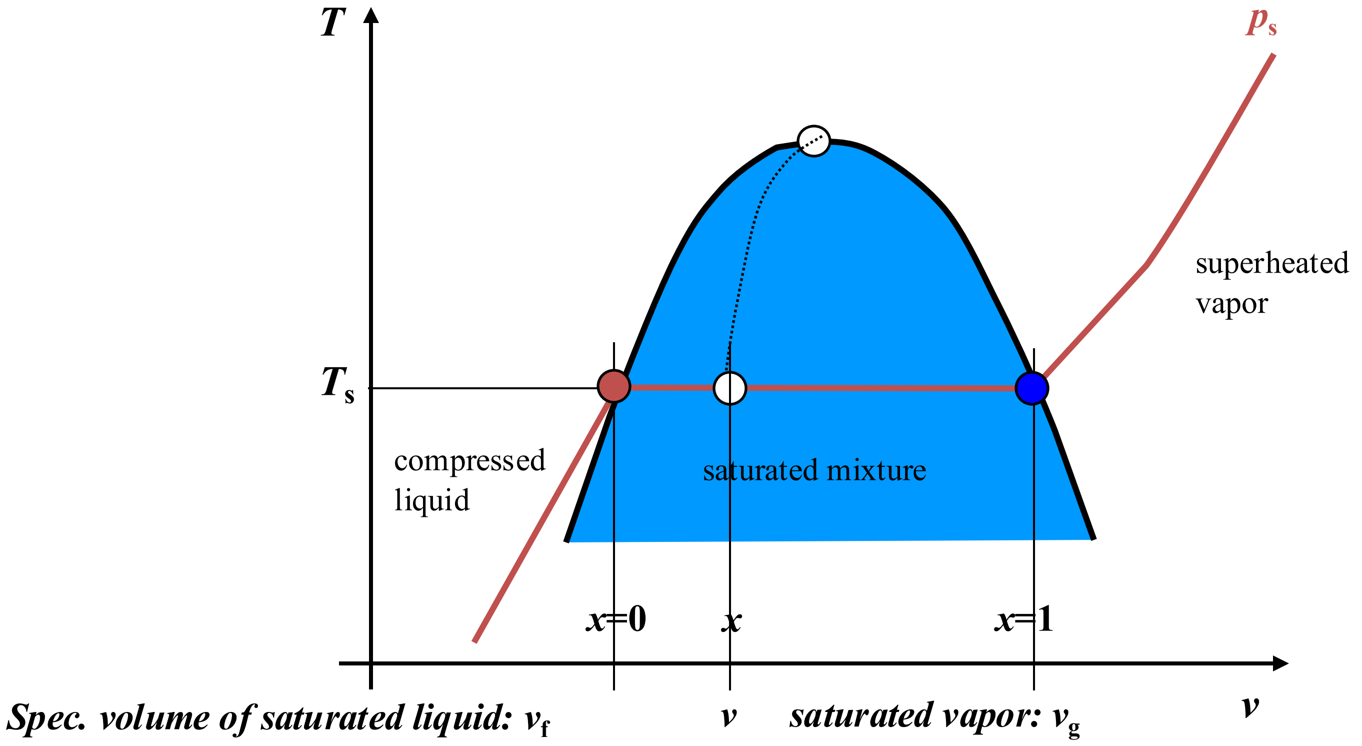
Two-Phase Liquid-Vapor Mixture





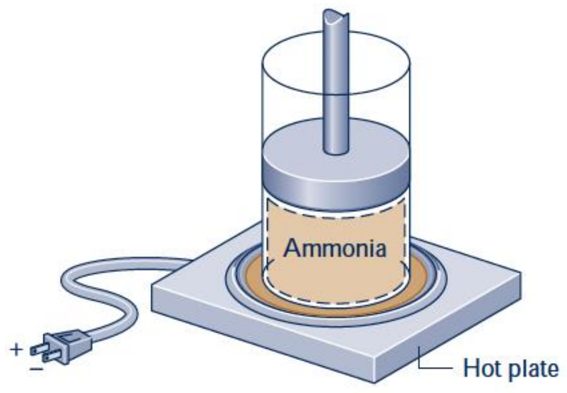
Quality

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



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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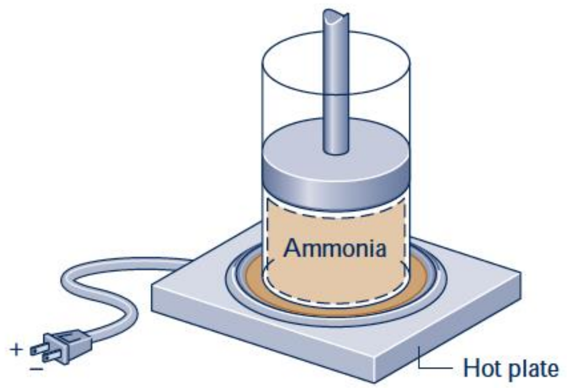
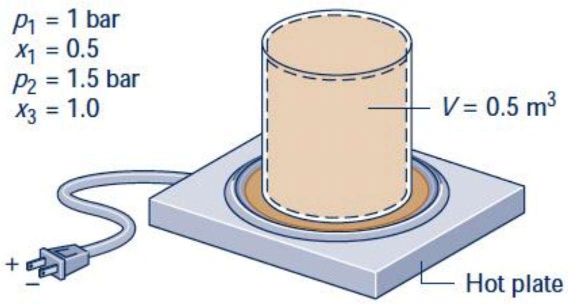


Example 3.2 in Moran

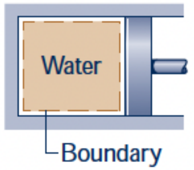
- A closed, rigid container of fixed volume is placed on a hot plate. Initially, at state 1, the container holds a two-phase mixture of saturated liquid water and saturated water vapor at $p_1 = 1$ **bar** with a **quality of 0.5**.
- After heating, at state 2, the pressure in the container is $p_2 = 1.5$ **bar**. Finally, with further heating, at state 3, the container only contains **saturated vapor**.
- **Indicate states 1-3 on a T-v diagram**



Example 3.4 in Moran

- Water contained in a piston–cylinder assembly undergoes two processes in series from an initial state where the pressure is 10 bar and the temperature is 400 ℃.
  - Process 1–2: The water is cooled as it is compressed at a constant pressure of 10 bar to the saturated vapor state.
  - Process 2–3: The water is cooled at constant volume to 150 ℃.

Sketch both processes on T–v and p–v diagrams.



Property Tables

- How to determine properties?
- Using property tables, for:
  - Compressed liquid (e.g., Table-A5)
  - Superheated vapor (e.g., Table-A2, A3)
  - Saturated liquid-vapor mixture (e.g., Table-A4)

Property Tables

Properties of Compressed Liquid Water

T °C	$v \times 10^3$ m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	$v \times 10^3$ m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 25 bar = 2.5 MPa (T_{sat} = 223.99°C)				p = 50 bar = 5.0 MPa (T_{sat} = 263.99°C)			
20	1.0006	83.80	86.30	.2961	.9995	83.65	88.65	.2956
40	1.0067	167.25	169.77	.5715	1.0056	166.95	171.97	.5705
80	1.0280	334.29	336.86	1.0737	1.0268	333.72	338.85	1.0720
100	1.0423	418.24	420.85	1.3050	1.0410	417.52	422.72	1.3030
140	1.0784	587.82	590.52	1.7369	1.0768	586.76	592.15	1.7343
180	1.1261	761.16	763.97	2.1375	1.1240	759.63	765.25	2.1341
200	1.1555	849.9	852.8	2.3294	1.1530	848.1	853.9	2.3255
220	1.1898	940.7	943.7	2.5174	1.1866	938.4	944.4	2.5128
Sat.	1.1973	959.1	962.1	2.5546	1.2859	1147.8	1154.2	2.9202

Property Tables

- How to determine properties from tables:
  - Linear interpolation of desired property (*u*, *v*, *s*, *h*, …) for desired temperature, pressure, … (*z*):

$$f(z) = \frac{f(z_2) - f(z_1)}{z_2 - z_1}(z - z_1) + f(z_1)$$

Moran 3.8.1

- **Instead of tables, we can also use databases online, e.g.:**
  - http://www.coolprop.org/

Sample Code

- https://colab.research.google.com/drive/1x1MU3CXz5fMMe7nZgiKsZopjYz2jvvQ1?usp=sharing

- Read the manual before using the package

http://www.coolprop.org/coolprop/HighLevelAPI.html#propssi-function