

CAE 208 Thermal-Fluids Engineering I

MMAE 320: Thermodynamics

Fall 2022

September 20, 2022

Properties of Pure Substances (I)

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ANNOUNCEMENTS

Announcement

- Assignment 2 feedback:
 - Do not confuse yourself
 - Pay attention to units (e.g., adding Pa to kPa without any conversion)
 - Make sure to start with the schematic (e.g., $12\text{cm}/\sin 30 = 24\text{ cm}$ vs 12cm)
 - Overall, great job!

Announcement

- Assignment 2 is graded (solution is also provided)
- Do not forget about assignment 3 submission this coming Thursday
- Assignment 4 will be posted on Thursday
- Think about the first midterm exam (currently is scheduled on October 13)

Announcement



Mechanical Design Advise & Professional Networking

SPEAKER

Mechanical Designer **Aaron Horta**

WHEN

September 22nd, 2022
12:40pm – 1:40pm

WHERE

John T. Rettaliata
Engineering Center,
RE 124

TALK ABOUT

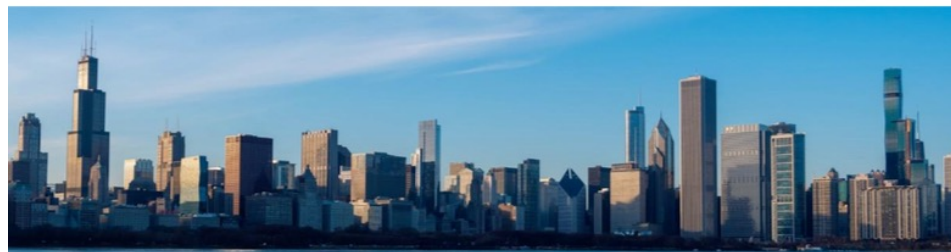
- ✓ Work Experiences
- ✓ Mechanical Design
- ✓ Tips & IIT Courses

For more information,
feel free to contact
ASHRAE official email
ashrae_iit@iit.edu



Interested in Joining

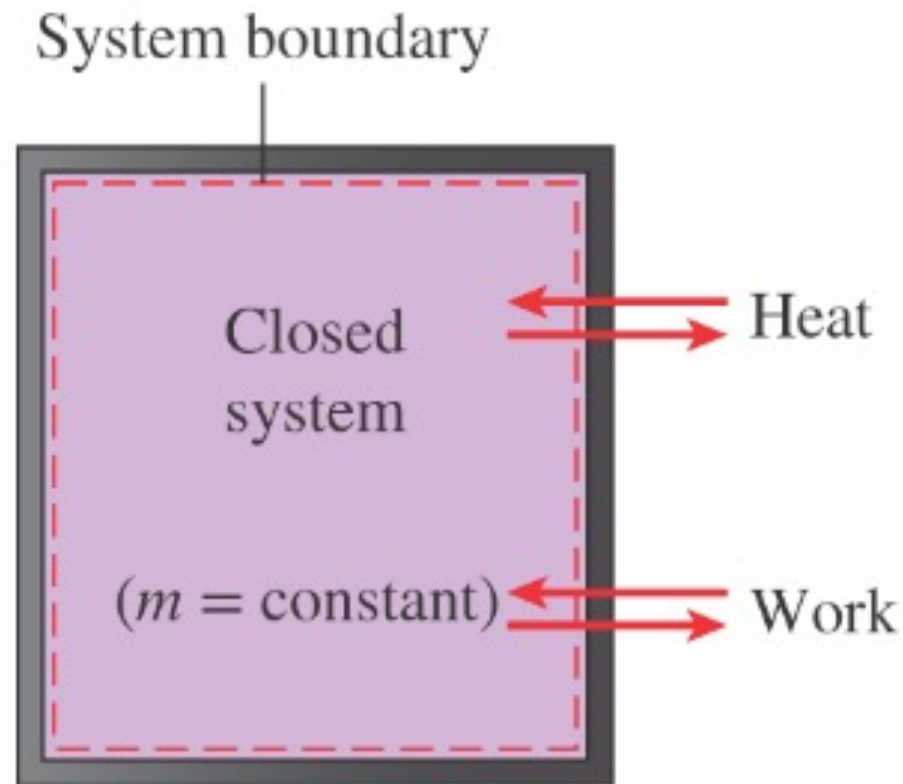
Lunch will be provided!



RECAP

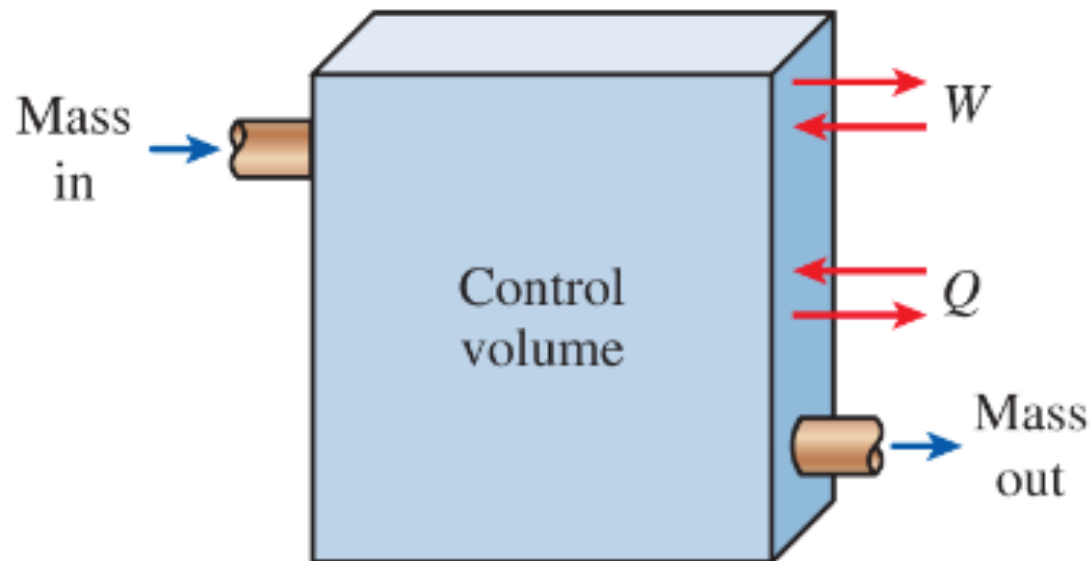
Recap

- Energy can cross the boundary of a closed system in two distinct forms:
 - Heat
 - Work



Recap

- Mechanisms of energy transfer, E_{in} and E_{out} :
 - The only two forms of energy interactions associated with a fixed mass or closed system are heat transfer and work



Recap

- We can sum the heat, work, and mass, and the heat transfer:

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{system}$$

Net energy transfer by heat, work, and mass

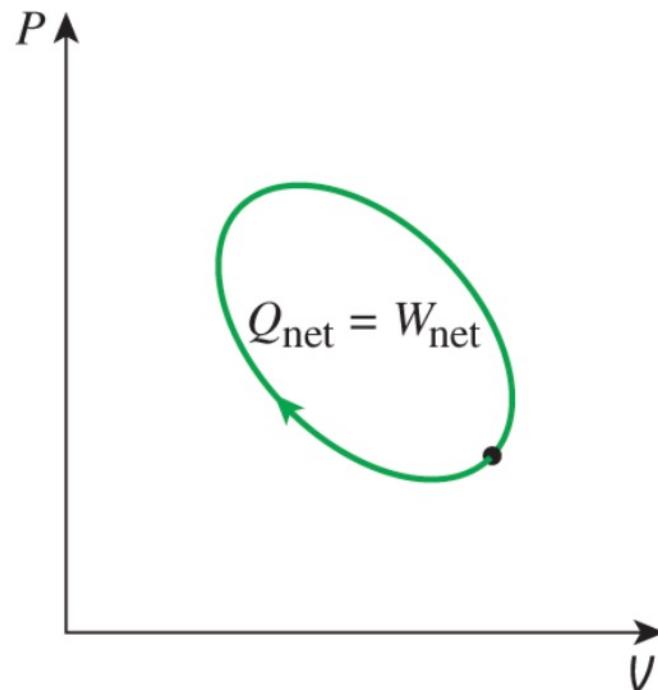
Change in internal, kinetic, potential, ..., energies

Recap

- For a closed system undergoing a cycle, the initial and final states are identical:

$$\Delta E = E_{in} - E_{out} = 0 \quad \rightarrow \quad E_{in} = E_{out}$$

$$W_{net,out} = Q_{net,in} \quad \rightarrow \quad \dot{W}_{net,out} = \dot{Q}_{net,in}$$



Recap

- Efficiency, in general, can be expressed in terms of the desired output and the required input as:

$$\textit{Efficiency} = \frac{\textit{Desired output}}{\textit{Required input}}$$

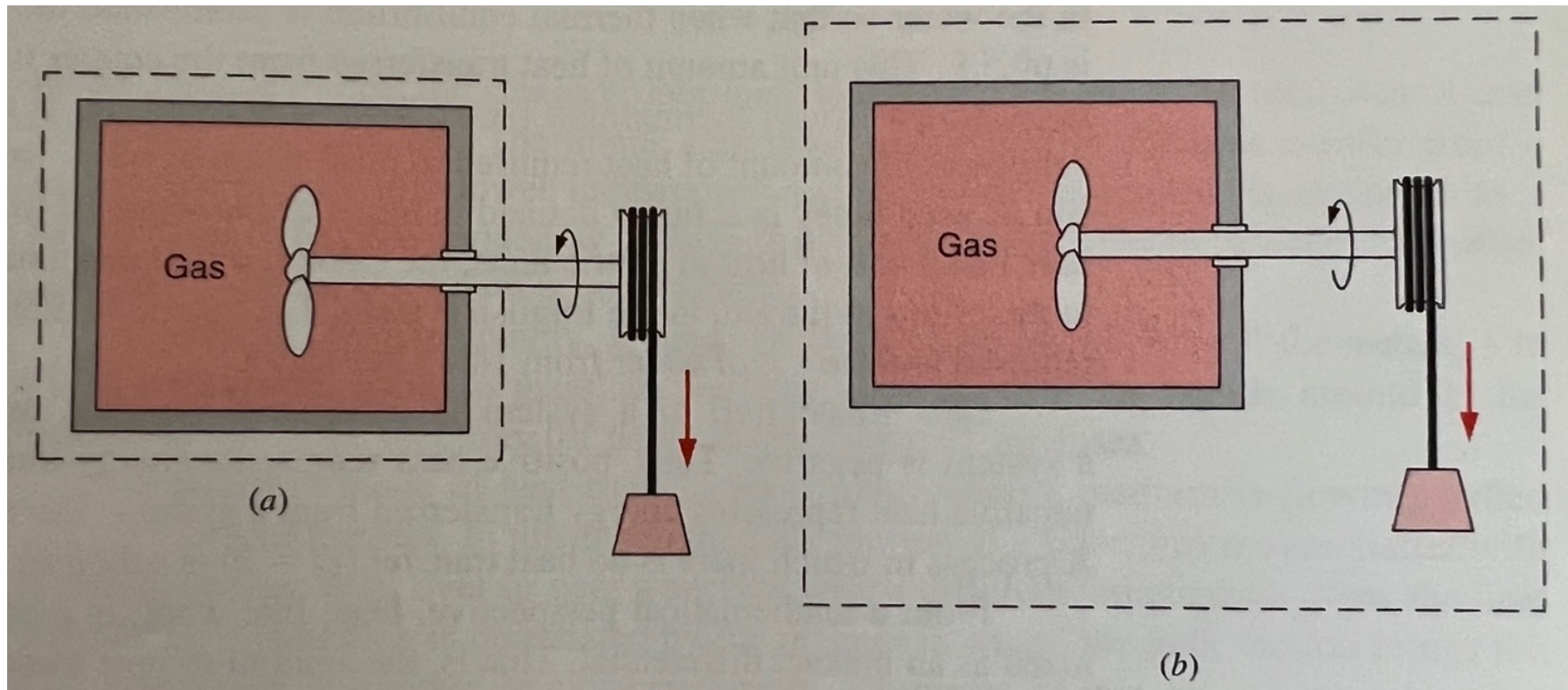
Recap

- Summarize efficiencies:

$$\eta_{mech} = \frac{\textit{mechanical energy output}}{\textit{Mechanical energy input}} = \frac{E_{mech,out}}{E_{mech,in}} = 1 - \frac{E_{mech,loss}}{E_{mech,in}}$$

Recap

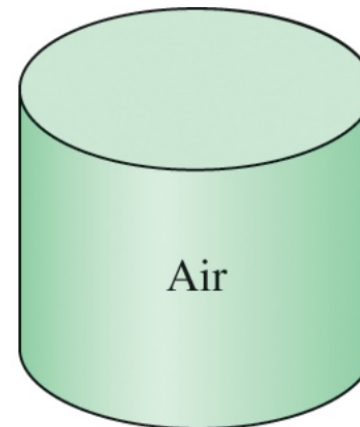
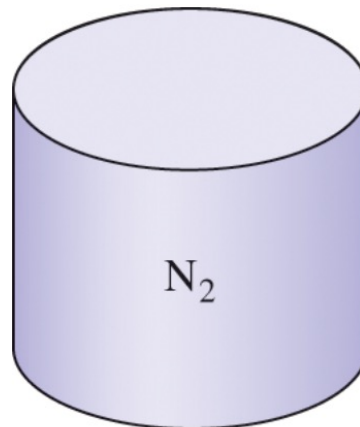
- What's the answer to last week's quiz?



PURE SUBSTANCE

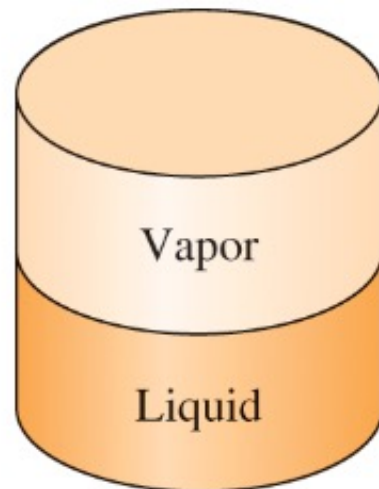
Pure Substance

- **Pure substance:** A substance that has a fix chemical composition throughout (e.g., water, nitrogen, carbon dioxide):
 - ❑ Does not have to be a single chemical element or compound
 - ❑ A mixture of various chemical elements or compounds qualifies as a pure substance as long as the mixture is homogenous (e.g., air as a mixture of several gases)
 - ❑ A mixture of oil and water is not a pure substance (i.e., oil is not soluble in water)

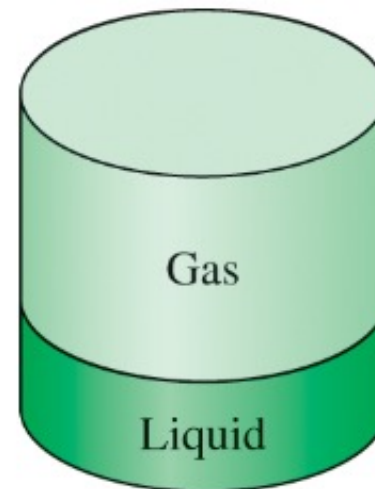


Pure Substance

- A mixture of two or more phases or a pure substance is still a pure substance as long as the chemical composition of all phases is the same:
 - ❑ A mixture of ice and liquid water for example is a pure substance
 - ❑ A mixture of liquid and gaseous air is not a pure substance



(a) H_2O



(b) Air

PHASES OF A PURE SUBSTANCE

Phases of a Pure Substance

- We all know from experience substances in different phases (e.g., at room temperature and pressure)
 - Copper
 - Mercury
 - Nitrogen
- Under different conditions, each may appear in different phases

Phases of a Pure Substance

- We have three principal phases
 - Solid
 - Liquid
 - Gas

Phases of a Pure Substance

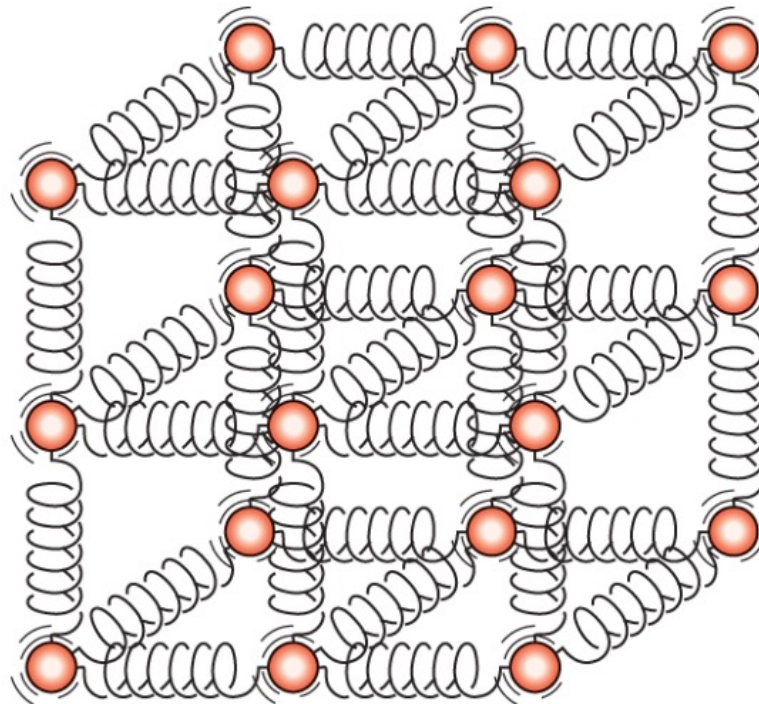
- A substance may have several phases within a principal phase each with a different molecular structure
 - ❑ Carbon (two solid phases): Graphite or diamond
 - ❑ Helium (two liquid phases)
 - ❑ Iron (three solid phases)
 - ❑ Ice (seven different phases at high pressure)
- A phase is identified as having distinct molecular arrangement that is homogenous throughout and separated from others by easily identifiable boundary surfaces (e.g., H₂O)

Phases of a Pure Substance

- Intermolecular bonds are strongest in solids and weakest in gases

Phases of a Pure Substance

- Solid:
 - ❑ Molecules are arranged in a three-dimensional pattern (lattice) that is repeated throughout
 - ❑ Small distances between molecules in a solid the attractive forces of molecules on each other are large and keep the molecules at fixed positions

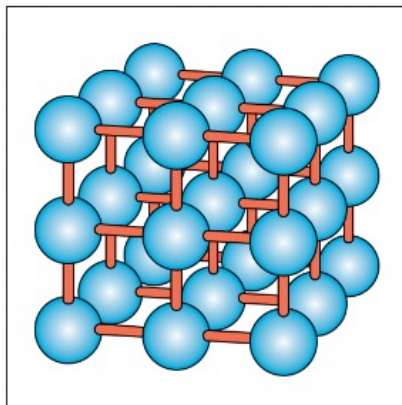


Phases of a Pure Substance

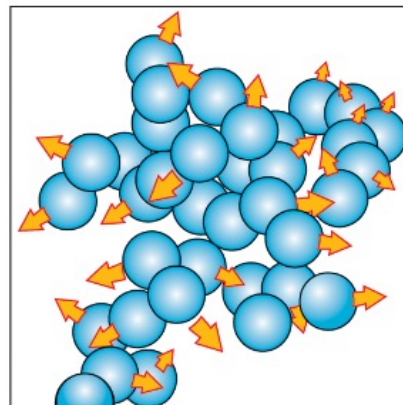
- Solid:
 - Molecules cannot move relative to each other, but they continually oscillate about their equilibrium positions
 - Velocity of the molecules during these oscillations depends on the temperature
 - At high temperatures, the velocity of the molecules reach a point where the intermolecular forces are partially overcome and groups of molecules break away (i.e., melting)

Phases of a Pure Substance

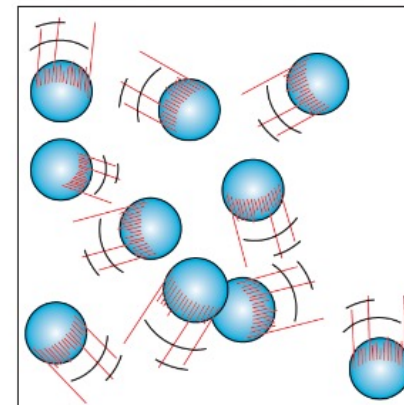
- Liquid:
 - ❑ Molecular spacing is not much different from that of the solid phase except the molecules are no longer at fixed positions relative to each other and they can rotate and translate freely
 - ❑ Intermolecular forces are weaker relative to solids but still relatively strong compared to the gases



(a)



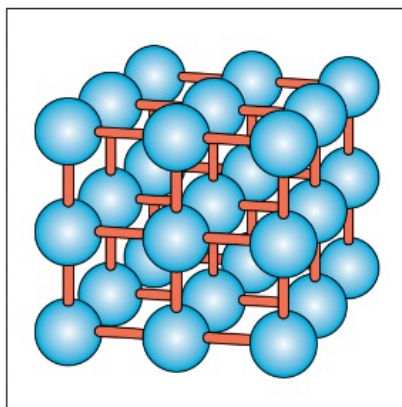
(b)



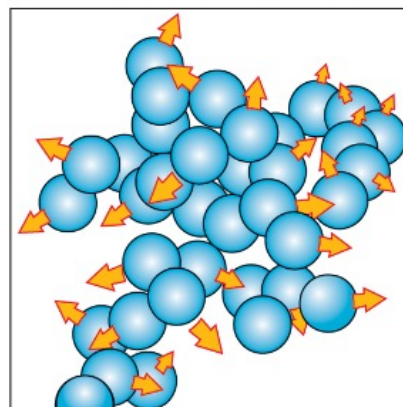
(c)

Phases of a Pure Substance

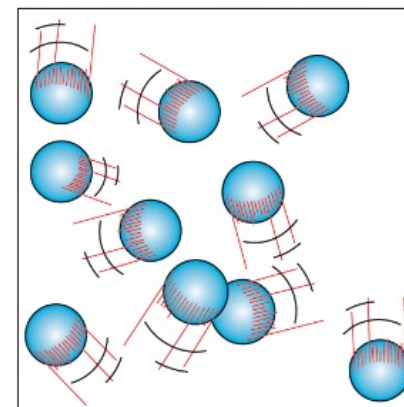
- Gas:
 - ❑ Molecules spacing are far apart from each other and molecular order is nonexistent
 - ❑ Gas molecules move about a random continually colliding with each other and the walls of the container they are in
 - ❑ At low densities, the intermolecular forces are very small, and collisions are the only mode of interactions between molecules



(a)



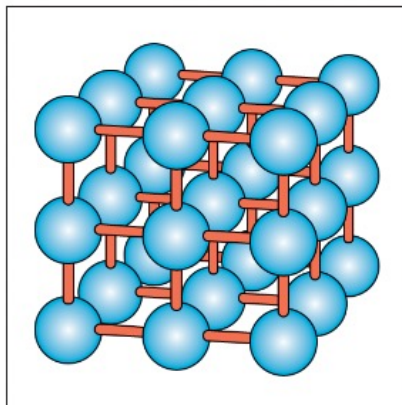
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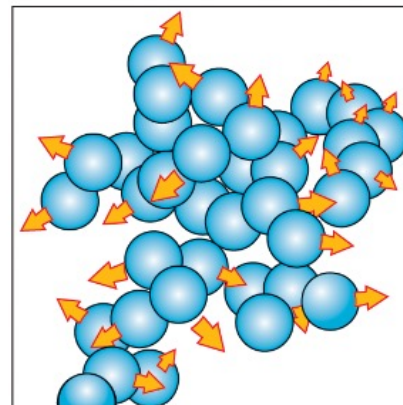
(c)

Phases of a Pure Substance

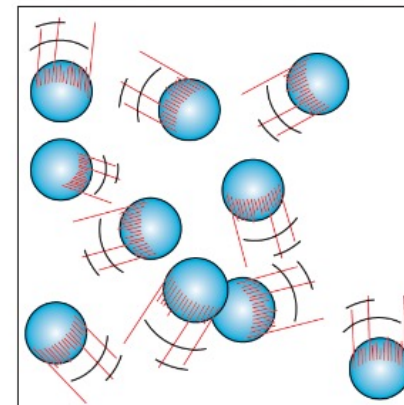
- Gas:
 - Molecules in the gas phase are a considerably higher energy level than they are in the liquid and solid phases, meaning the gas must release a large amount of its energy before it can condensate or freeze



(a)



(b)



(c)

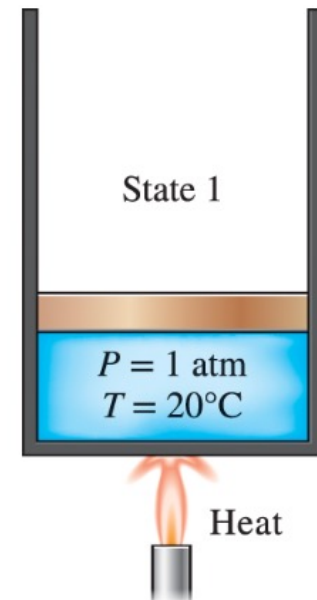
PHASE CHANGE PROCESS OF PURE SUBSTANCES

Phase Change Processes of Pure Substances

- There are many practical situations where two phases of a pure substance co-exist in equilibrium
 - Water as a mixture of liquid and vapor in the boiler and the condenser of a steam power plant
 - Refrigerant turns from liquid to vapor in the freezer of a refrigerator

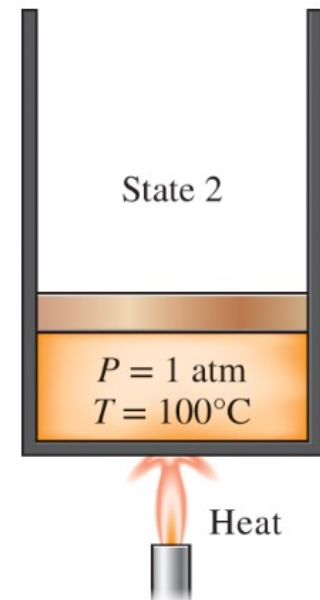
Phase Change Processes of Pure Substances

- Compressed liquid (subcooled liquid):
 - At 20 °C and 1 atm pressure
 - Meaning it not about to vaporize



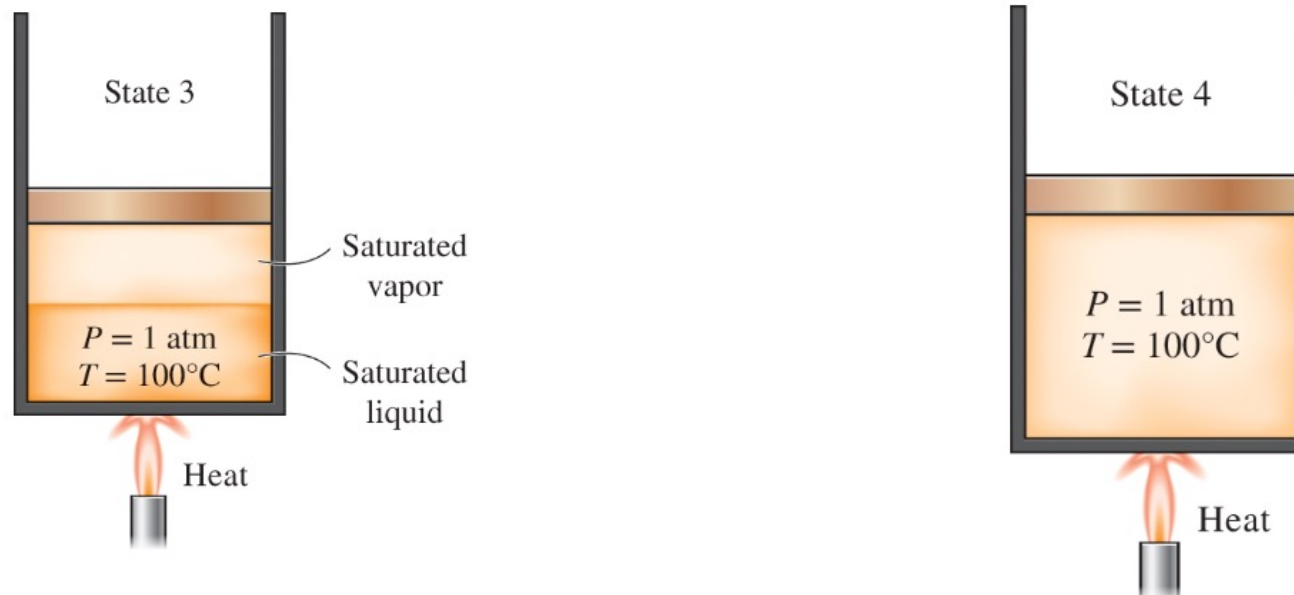
Phase Change Processes of Pure Substances

- Saturated liquid:
 - More heat is transferred, and the temperature reaches to 100 °C (about to vaporize)
 - Any additional heat will cause some liquid to vaporize (phase change process)



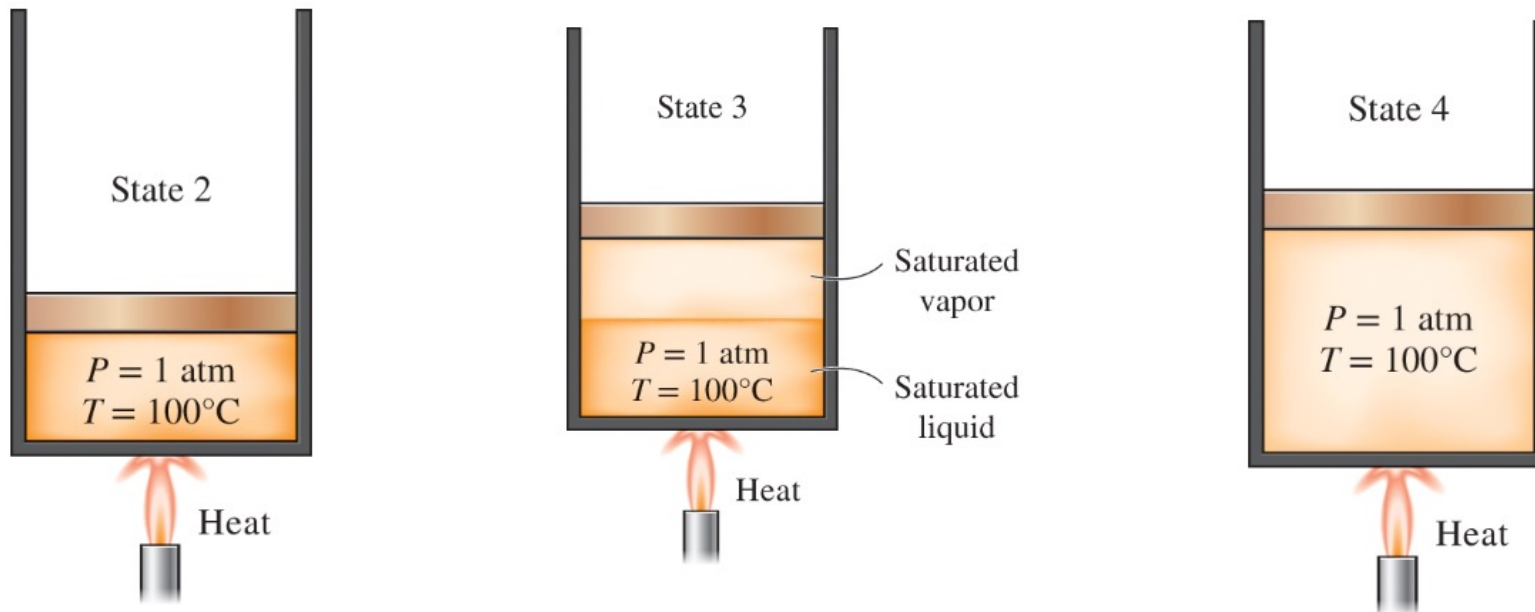
Phase Change Processes of Pure Substances

- Saturated vapor
 - Once boiling starts, the temperature stop rising until the liquid is completely vaporized (temperature remains constant during the entire phase-change process if pressure is held constant)
 - A vapor that is about to condensate is called a saturated vapor



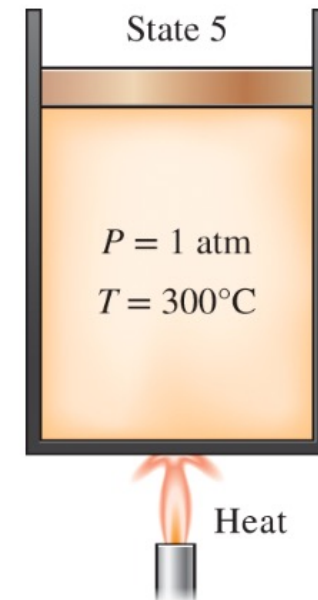
Phase Change Processes of Pure Substances

- Saturated liquid-vapor mixture



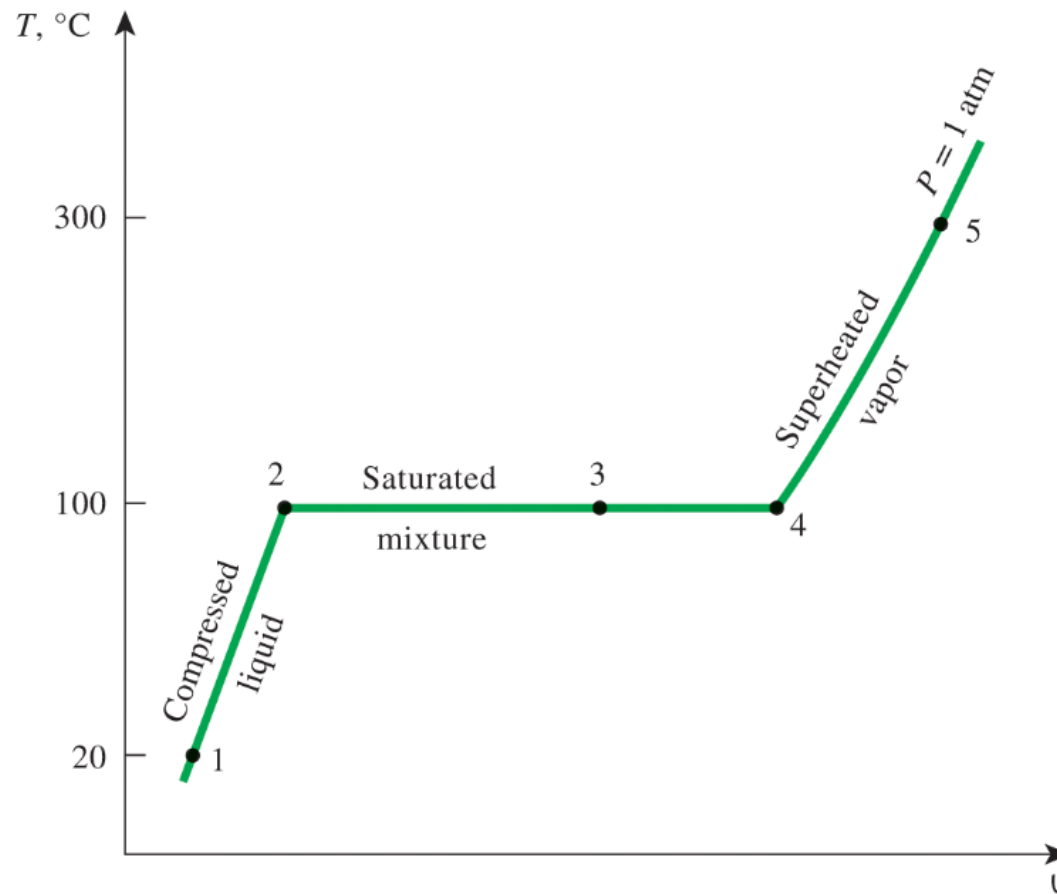
Phase Change Processes of Pure Substances

- Superheated vapor
 - A vapor is not about to condensate (i.e., not a saturated vapor)



Phase Change Processes of Pure Substances

- Now let's create the the T-v process diagram:



SATURATION TEMPERATURE AND SATURATION PRESSURE

Saturation Temperature and Pressure

- Water boils at 100 °C

Is this statement correct?

Saturation Temperature and Pressure

- The temperature at which water starts boiling depends on the pressure and therefore pressure is fixed, so the boiling temperature
- At a given pressure, the temperature at which a pure substance changes phase is called the saturation temperature (T_{sat}) (e.g., at a pressure of 101.325 kPa, T_{sat} is 99.97 °C)

What's the saturation pressure at a temperature of 99.7 °C?

Saturation Temperature and Pressure

- For water:

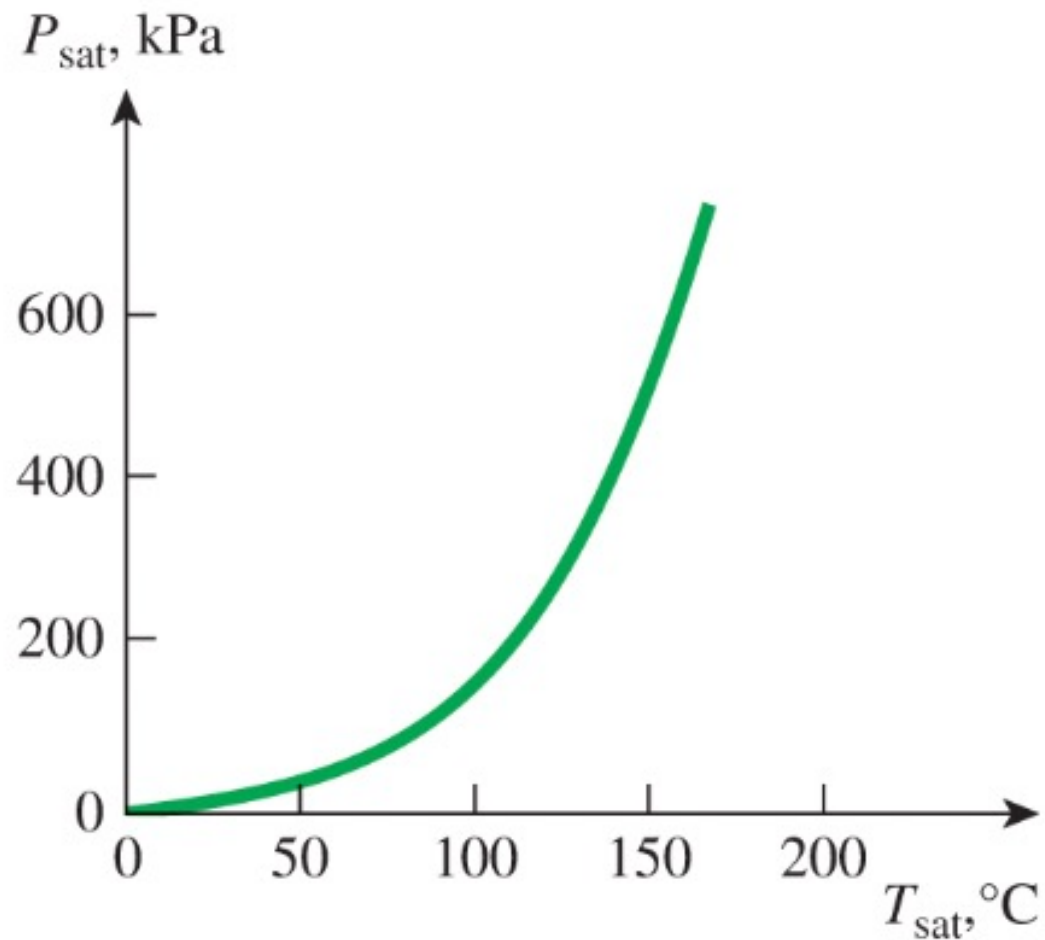
TABLE 4-1	
Saturation (or vapor) pressure of water at various temperatures	
Temperature T , °C	Saturation pressure P_{sat} , kPa
-10	0.260
-5	0.403
0	0.611
5	0.872
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581

Saturation Temperature and Pressure

- It takes a large amount of energy to melt a solid or vaporize a liquid. The amount of energy absorbed or released during a phase-change process is called the *latent heat*
 - ❑ The amount of energy absorbed during melting is called the *latent heat of fusion* is equivalent to the amount of energy released during freezing
 - ❑ The amount of energy absorbed during vaporization is called the *latent heat of vaporization* is equivalent to the amount of energy released during condensation

Saturation Temperature and Pressure

- The liquid-vapor saturation vapor of a pure substance:



Saturation Temperature and Pressure

- Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

TABLE 4-2

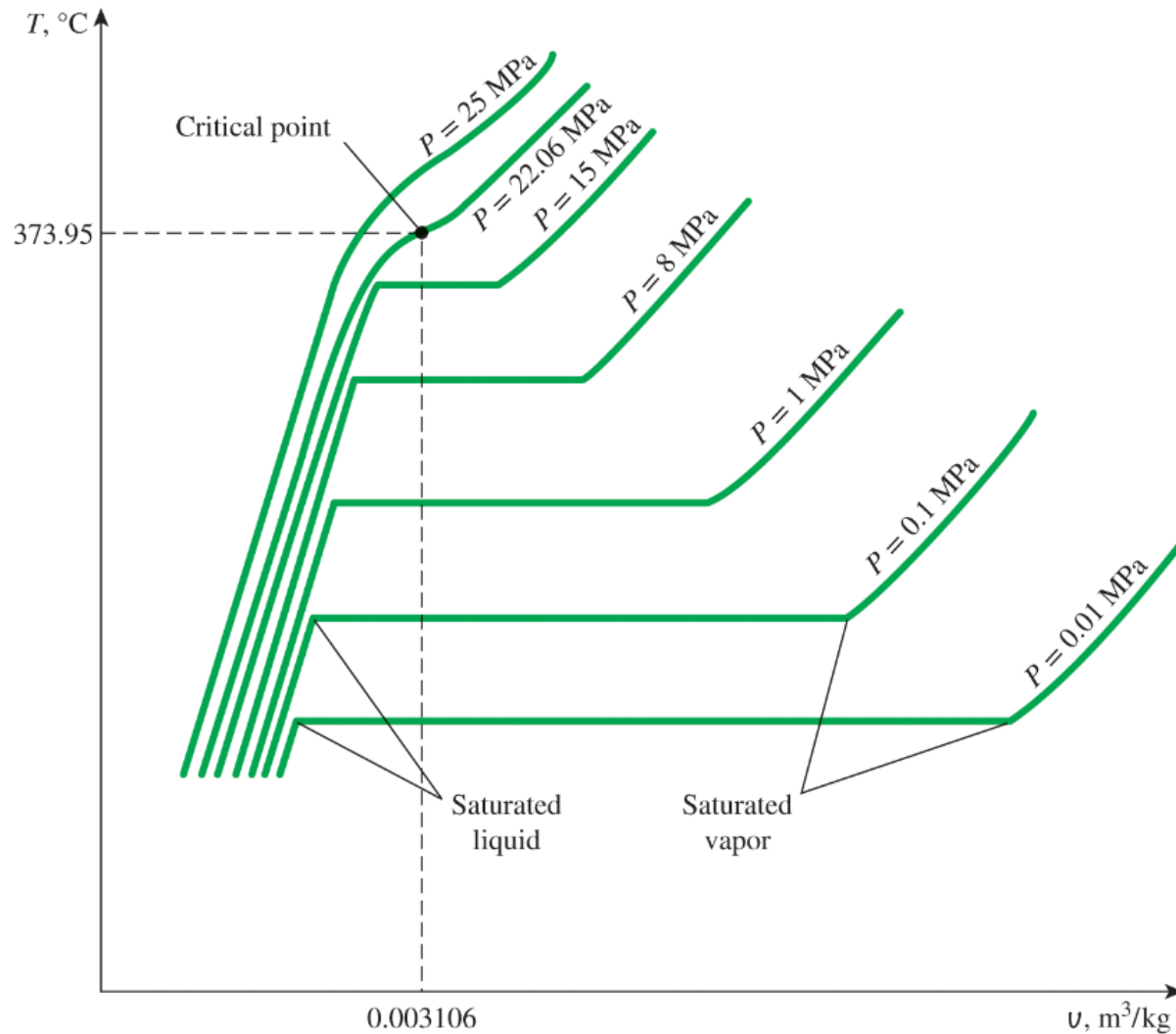
Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7

PROPERTY DIAGRAMS FOR PHASE- CHANGE PROCESSES

Property Diagrams For Phase-Change Processes

- We always look at the property diagrams in this course



Property Diagrams For Phase-Change Processes

- Critical point is the point at which the saturated liquid and saturated vapor states are identical
 - Critical pressure (P_{cr})
 - Critical temperature (T_{cr})
 - Critical specific volume (v_{cr})

Property Diagrams For Phase-Change Processes

- For the following materials

Material	P_{cr} (MPa)	T_{cr} (K)	v_{cr} (m³/kg)
Water	22.06	373.95	0.003106
Helium	0.23	-267.85	0.01444

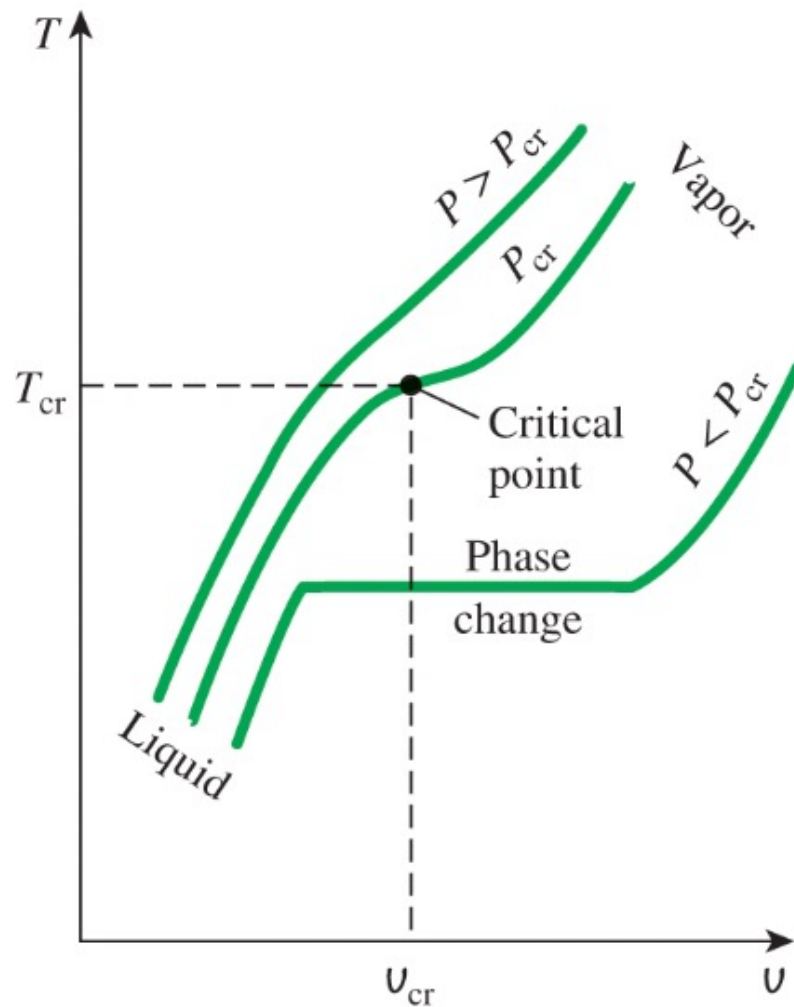
Property Diagrams For Phase-Change Processes

- Table A-1

TABLE A-1						
Molar mass, gas constant, and critical-point properties						
Substance	Formula	Molar mass, M kg/kmol	Gas constant, R kJ/kg · K*	Critical-point properties		
				Temperature, K	Pressure, MPa	Volume, m ³ /kmol
Air	—	28.97	0.2870	132.5	3.77	0.0883
Ammonia	NH ₃	17.03	0.4882	405.5	11.28	0.0724
Argon	Ar	39.948	0.2081	151	4.86	0.0749
Benzene	C ₆ H ₆	78.115	0.1064	562	4.92	0.2603
Bromine	Br ₂	159.808	0.0520	584	10.34	0.1355

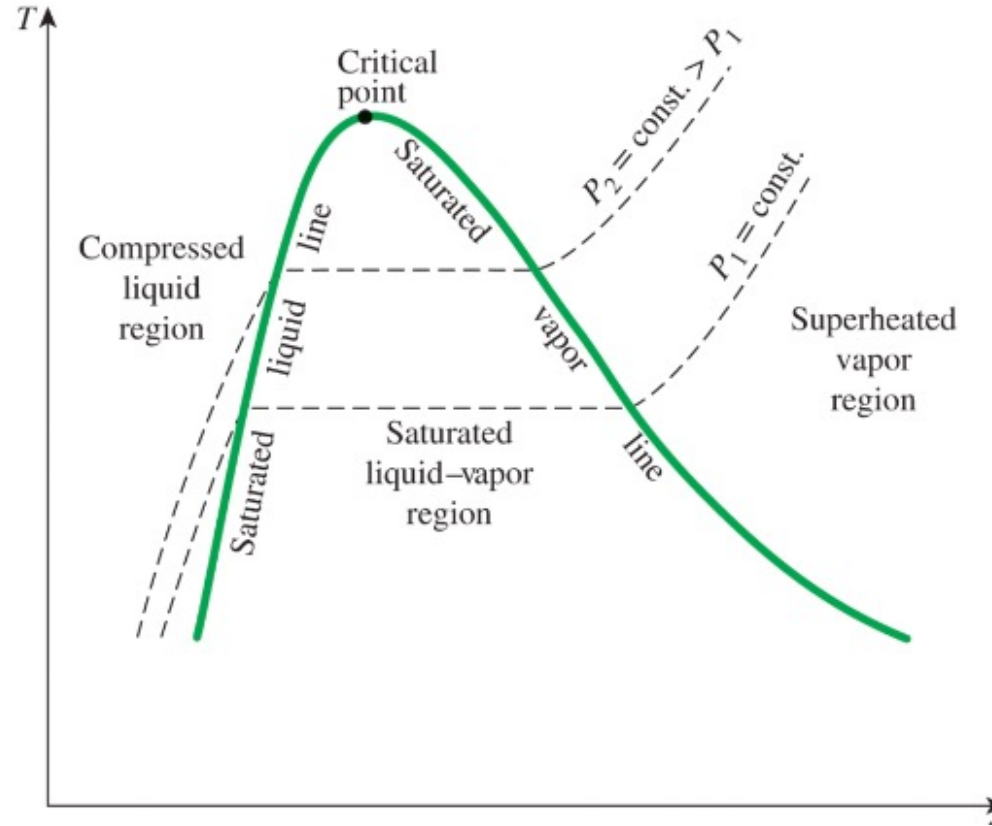
Property Diagrams For Phase-Change Processes

- At pressure above the critical pressure there is not a distinct phase-change process



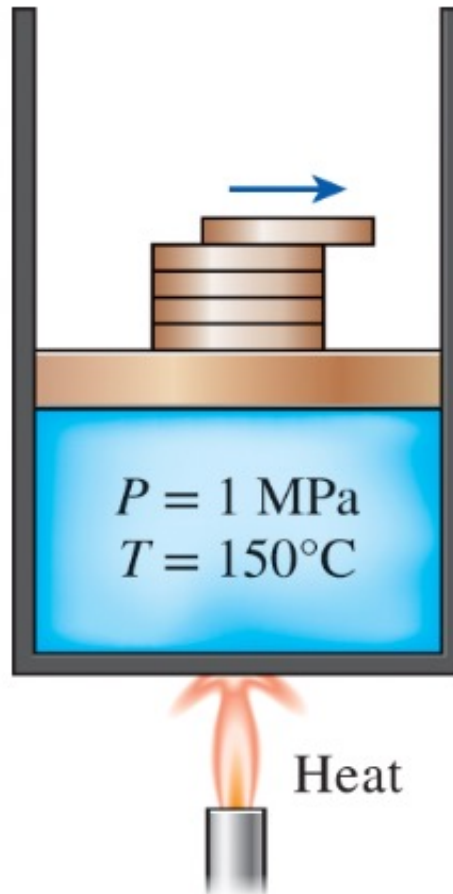
Property Diagrams For Phase-Change Processes

- The saturated liquid states can be connected by a line called saturated liquid line and similarly the saturated vapor line



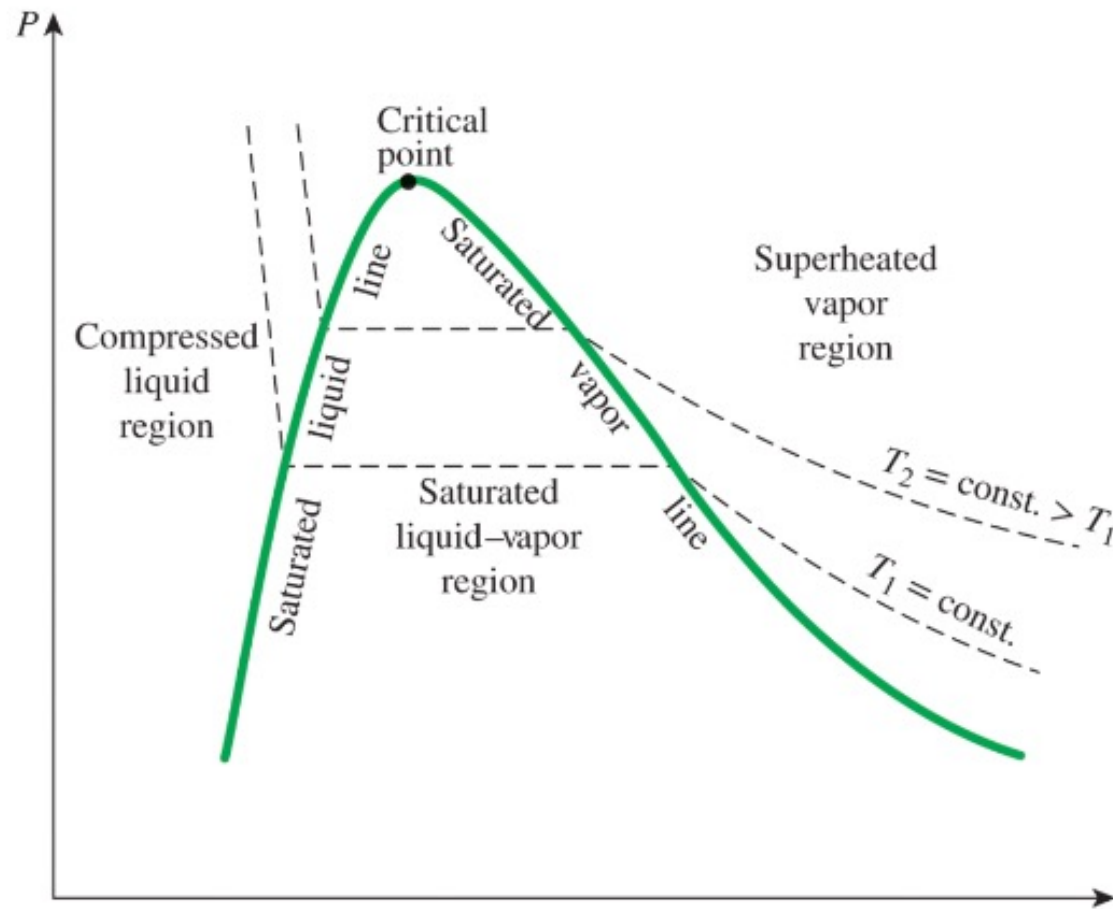
Property Diagrams For Phase-Change Processes

- Repeat the experiment to get the P-v diagram



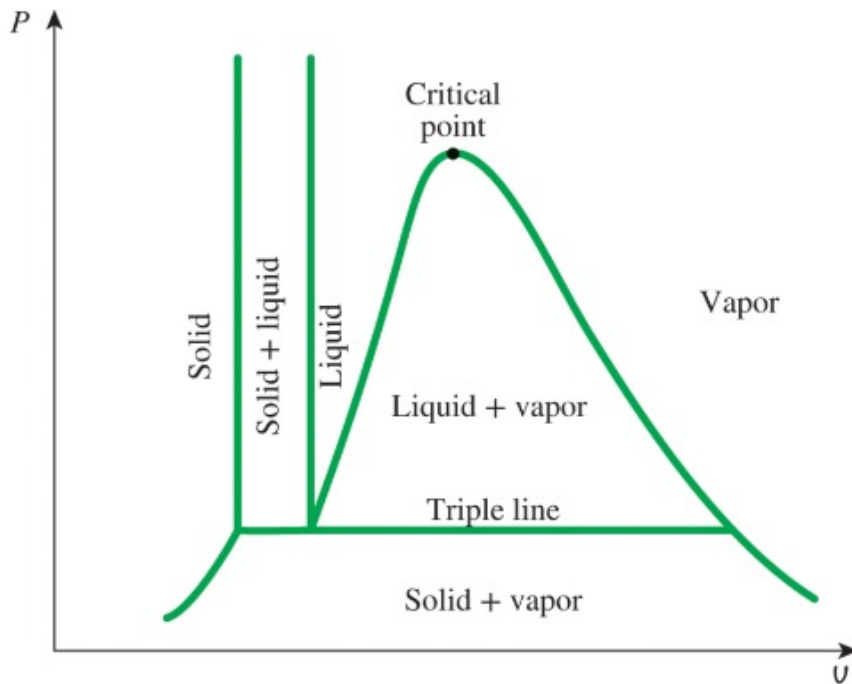
Property Diagrams For Phase-Change Processes

- The P-v diagram of a pure substance is very much like the T-v diagram but $T = \text{constant}$ lines on this diagram have a downward trend

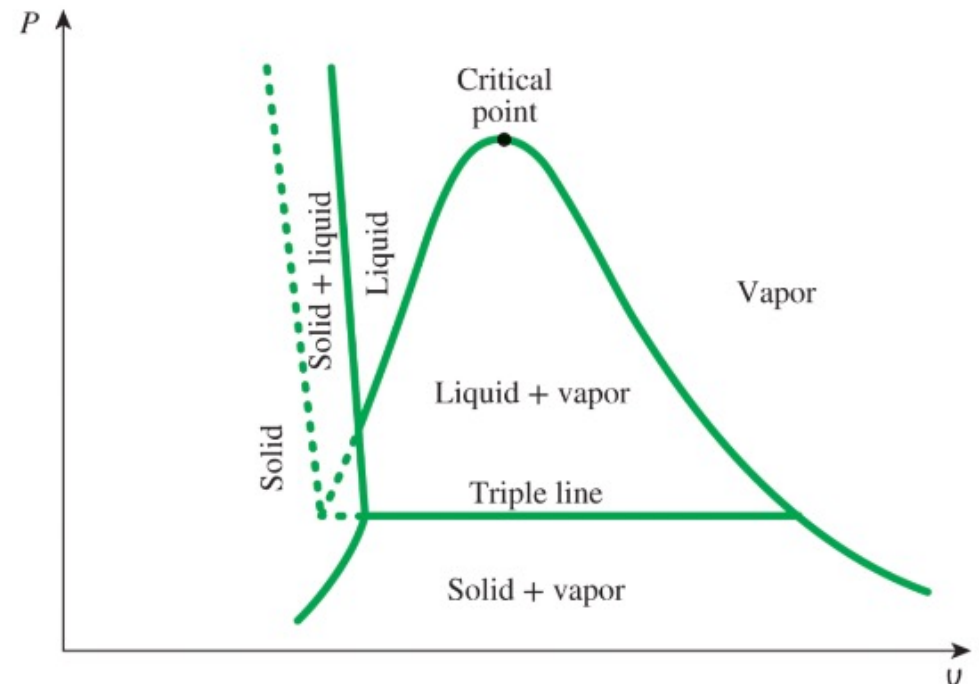


Property Diagrams For Phase-Change Processes

- Extending the diagram to include solid phase:



(a) P - U diagram of a substance that contracts on freezing



(b) P - U diagram of a substance that expands on freezing (such as water)

Property Diagrams For Phase-Change Processes

- The states on the triple line of a substance have the same pressure and temperature but different specific volumes



Property Diagrams For Phase-Change Processes

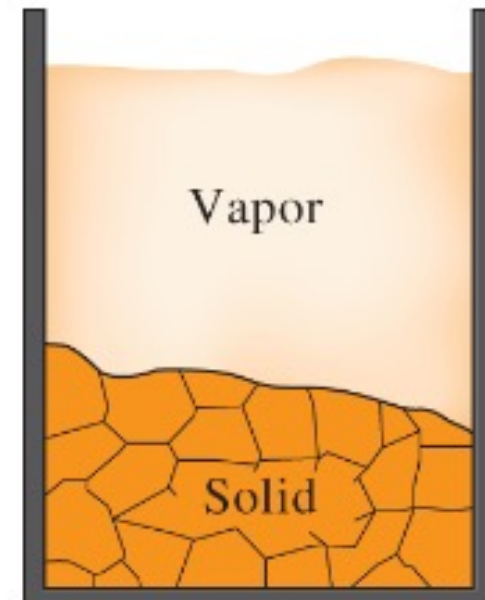
- Triple point temperatures and pressures of various substances:

TABLE 4-3
Triple-point temperatures and pressures of various substances

Substance	Formula	T_{tp} , K	P_{tp} , kPa
Acetylene	C ₂ H ₂	192.4	120
Ammonia	NH ₃	195.40	6.076
Argon	A	83.81	68.9
Carbon (graphite)	C	3900	10,100
Carbon dioxide	CO ₂	216.55	517
Carbon monoxide	CO	68.10	15.37
Deuterium	D ₂	18.63	17.1
Ethane	C ₂ H ₆	89.89	8×10^{-4}
Ethylene	C ₂ H ₄	104.0	0.12
Helium 4 (λ point)	He	2.19	5.1
Hydrogen	H ₂	13.84	7.04
Hydrogen chloride	HCl	158.96	13.9
Mercury	Hg	234.2	1.65×10^{-7}
Water	H ₂ O	273.16	0.61
Xenon	Xe	161.3	81.5
Zinc	Zn	692.65	0.065

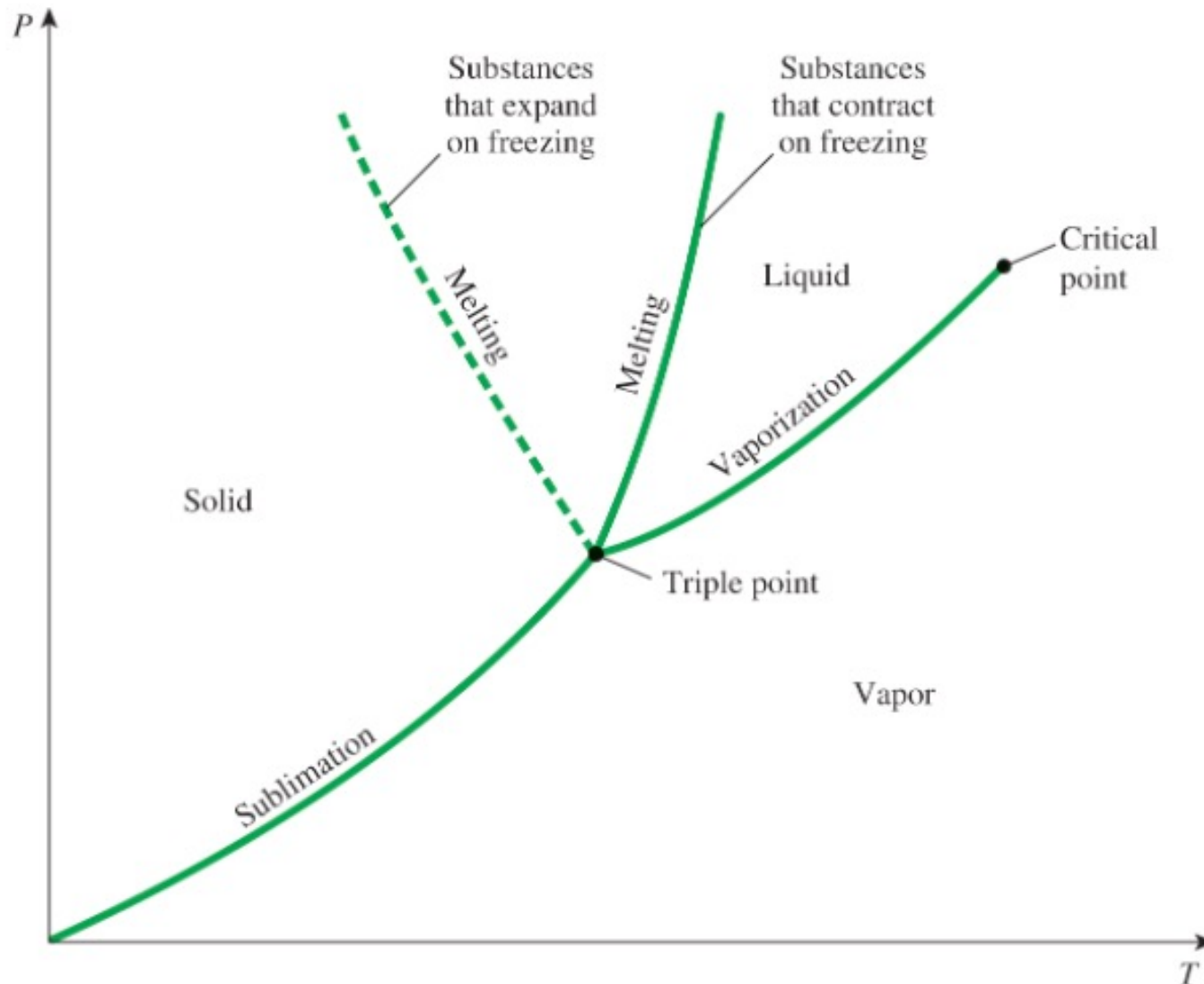
Property Diagrams For Phase-Change Processes

- There are two ways a substance can pass from the solid to the vapor phase:
 - ❑ It melts first into a liquid and subsequently evaporates
 - ❑ It evaporates directly without melting first known as sublimation (occurs below at the triple-point value since a pure substance cannot exist in the liquid phase at those pressure)



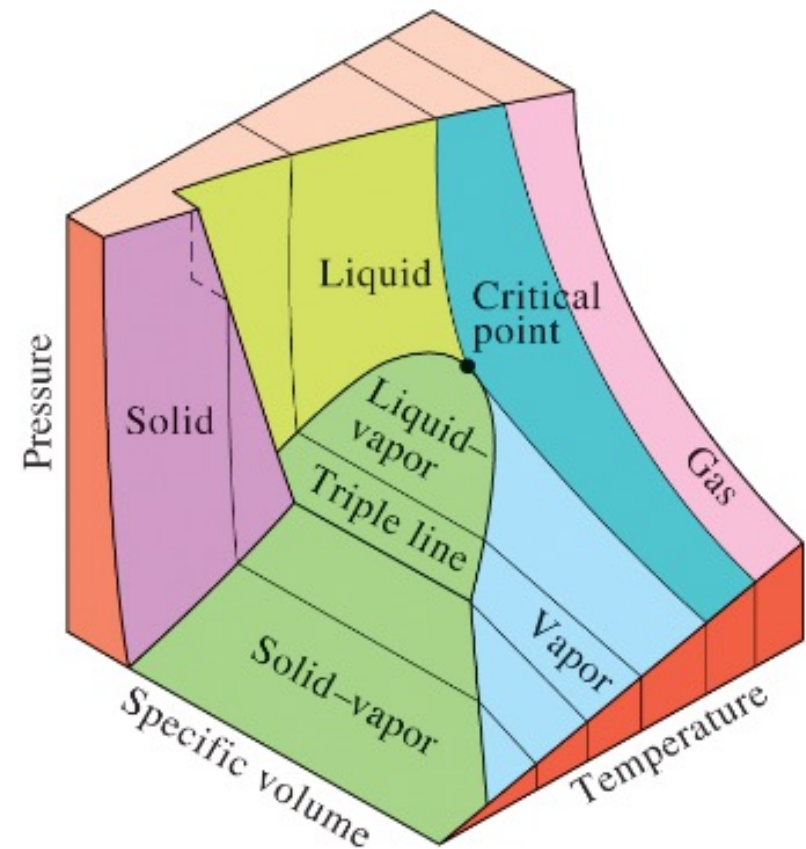
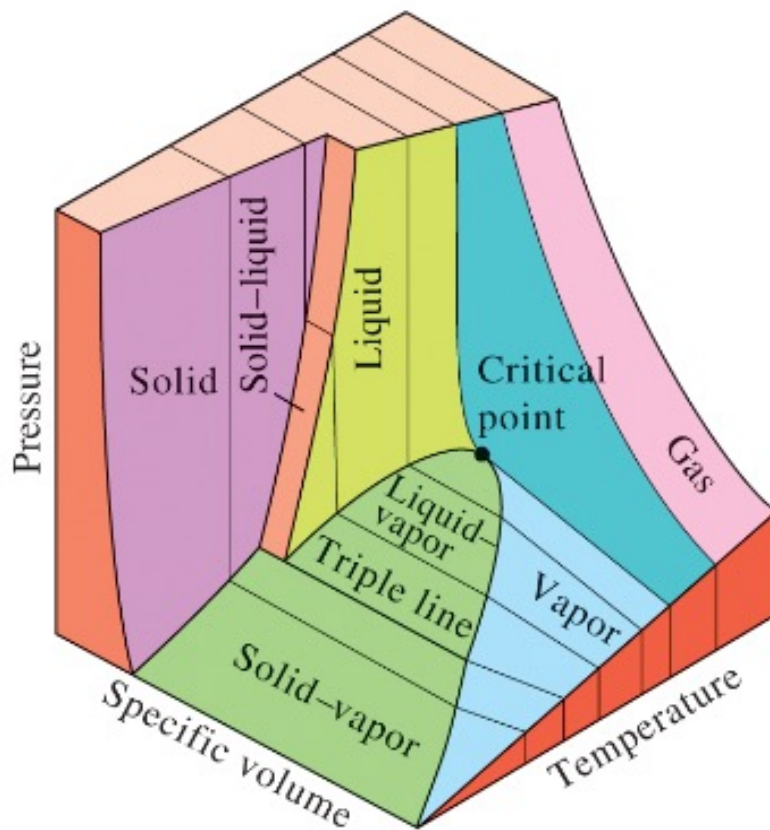
Property Diagrams For Phase-Change Processes

- P-T diagram is known as the phase diagram



Property Diagrams For Phase-Change Processes

- P-v-T diagram



CLASS ACTIVITY

Class Activity

- What's the common phase change in the atmospheric pressure for CO₂?

