

# Thermodynamics: An Engineering Approach

## 8th Edition

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## CHAPTER 3

# PROPERTIES OF PURE SUBSTANCES

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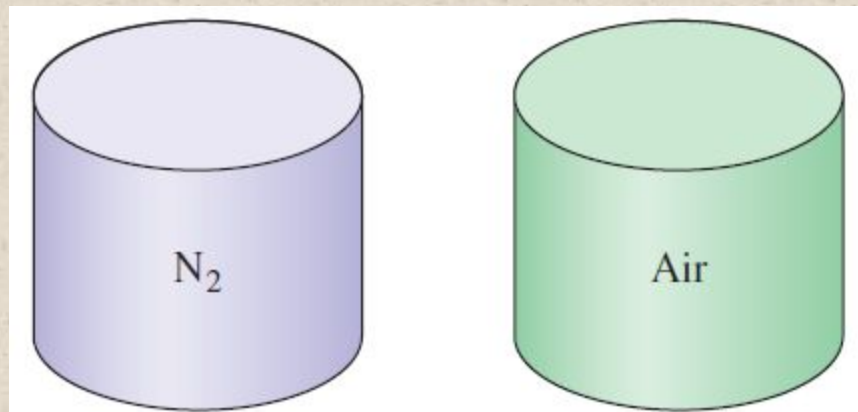
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# Objectives

- Introduce the concept of a pure substance.
- Discuss the physics of phase-change processes.
- Illustrate the  $P$ - $v$ ,  $T$ - $v$ , and  $P$ - $T$  property diagrams and  $P$ - $v$ - $T$  surfaces of pure substances.
- Demonstrate the procedures for determining thermodynamic properties of pure substances from tables of property data.
- Describe the hypothetical substance “ideal gas” and the ideal-gas equation of state.
- Apply the ideal-gas equation of state in the solution of typical problems.
- Introduce the compressibility factor, which accounts for the deviation of real gases from ideal-gas behavior.
- Present some of the best-known equations of state.

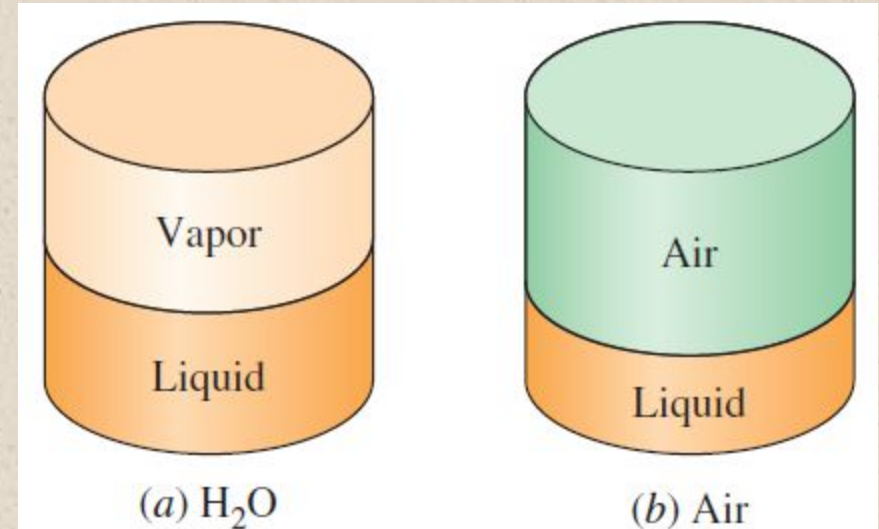
# ✓ PURE SUBSTANCE

- **Pure substance:** A substance that has a fixed chemical composition throughout.
- Air is a mixture of several gases, but it is considered to be a pure substance.



**FIGURE 3–1**

Nitrogen and gaseous air are pure substances.



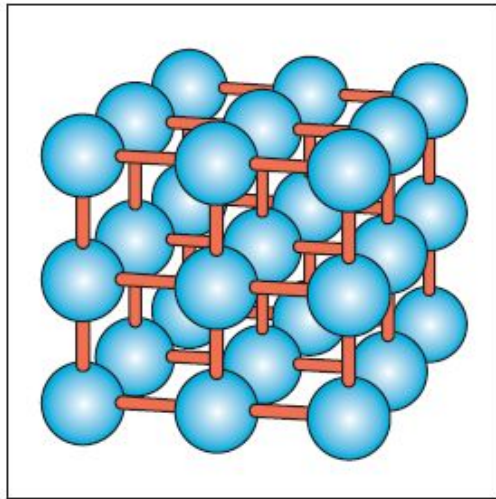
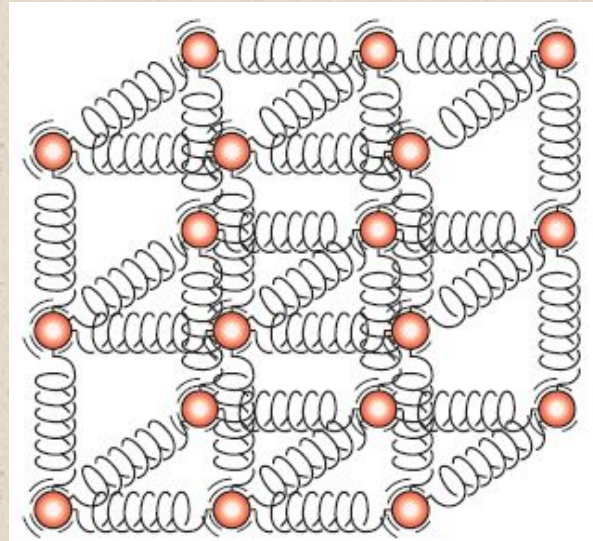
**FIGURE 3–2**

A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

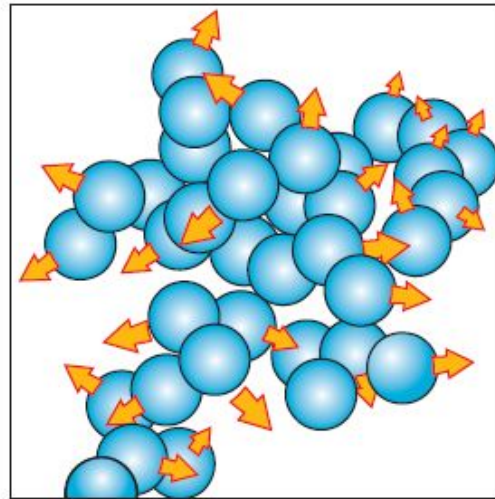


# PHASES OF A PURE SUBSTANCE

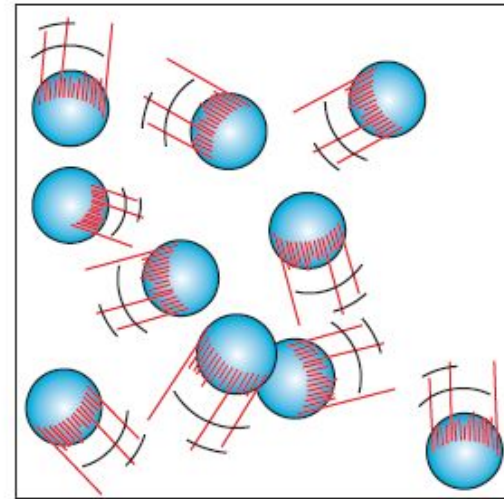
The molecules in a solid are kept at their positions by the large springlike inter-molecular forces.



(a)



(b)



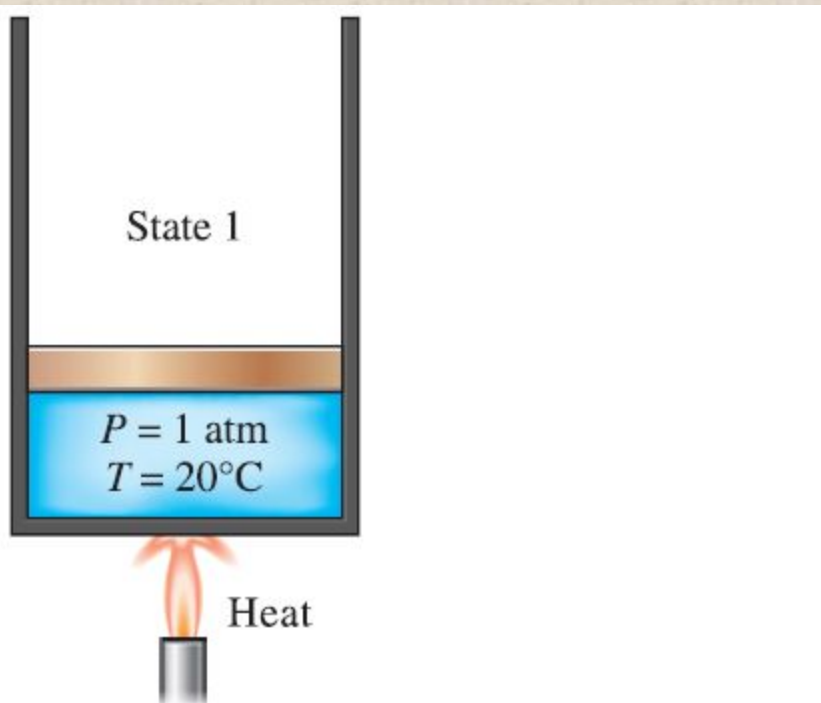
(c)

**FIGURE 3-4**

The arrangement of atoms in different phases: (a) molecules are at relatively fixed positions in a solid, (b) groups of molecules move about each other in the liquid phase, and (c) molecules move about at random in the gas phase.

# PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

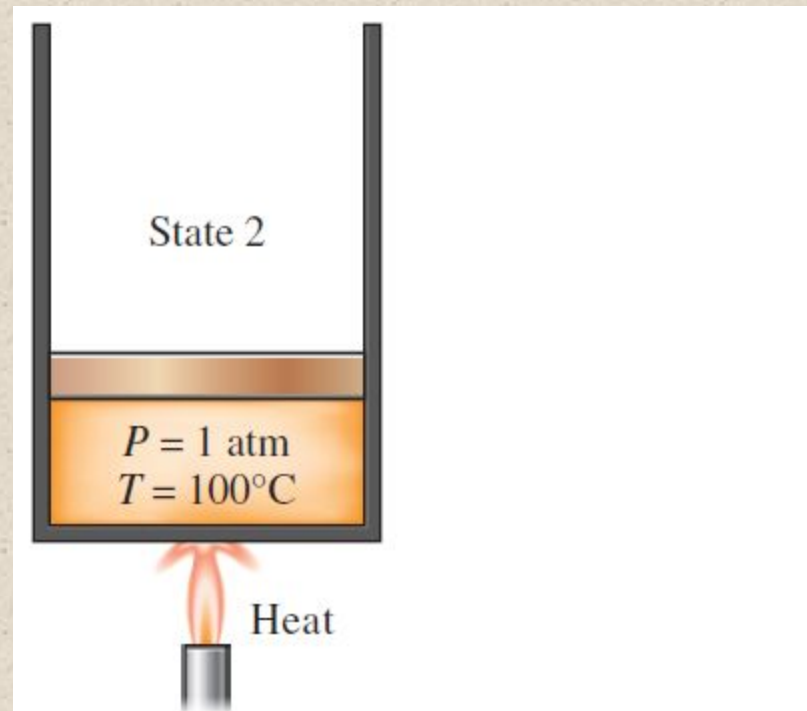
**Compressed liquid (subcooled liquid):** A substance that it is *not about to vaporize*



**FIGURE 3–5**

At 1 atm and  $20^\circ\text{C}$ , water exists in the liquid phase (*compressed liquid*).

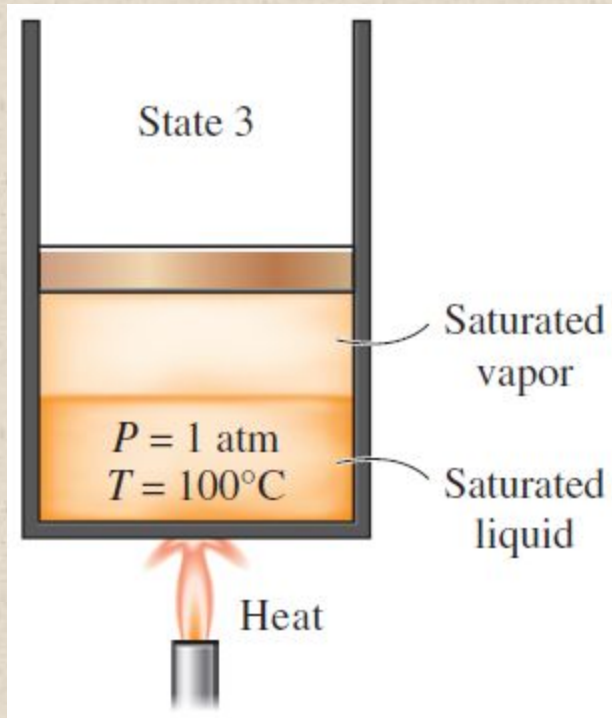
**Saturated liquid:** A liquid that is *about to vaporize*



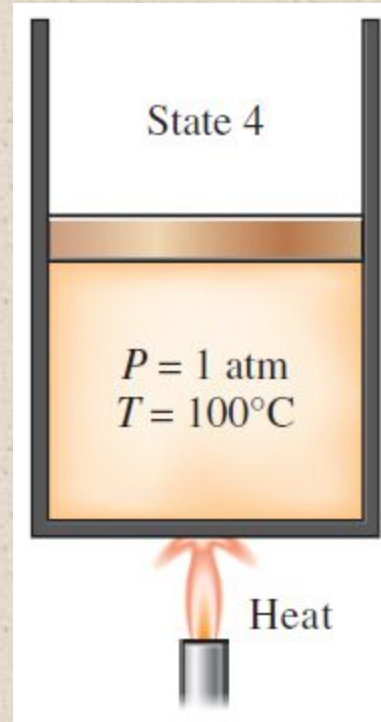
**FIGURE 3–6**

At 1 atm pressure and  $100^\circ\text{C}$ , water exists as a liquid that is ready to vaporize (*saturated liquid*).

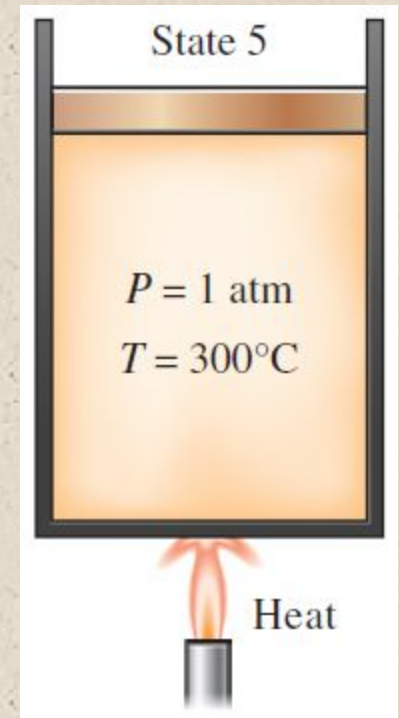
- **Saturated vapor**: A vapor that is *about to condense*.
- **Saturated liquid–vapor mixture**: The state at which the *liquid and vapor phases coexist* in equilibrium.
- **Superheated vapor**: A vapor that is *not about to condense* (i.e., not a saturated vapor).



As more heat is transferred, part of the saturated liquid vaporizes (**saturated liquid–vapor mixture**).



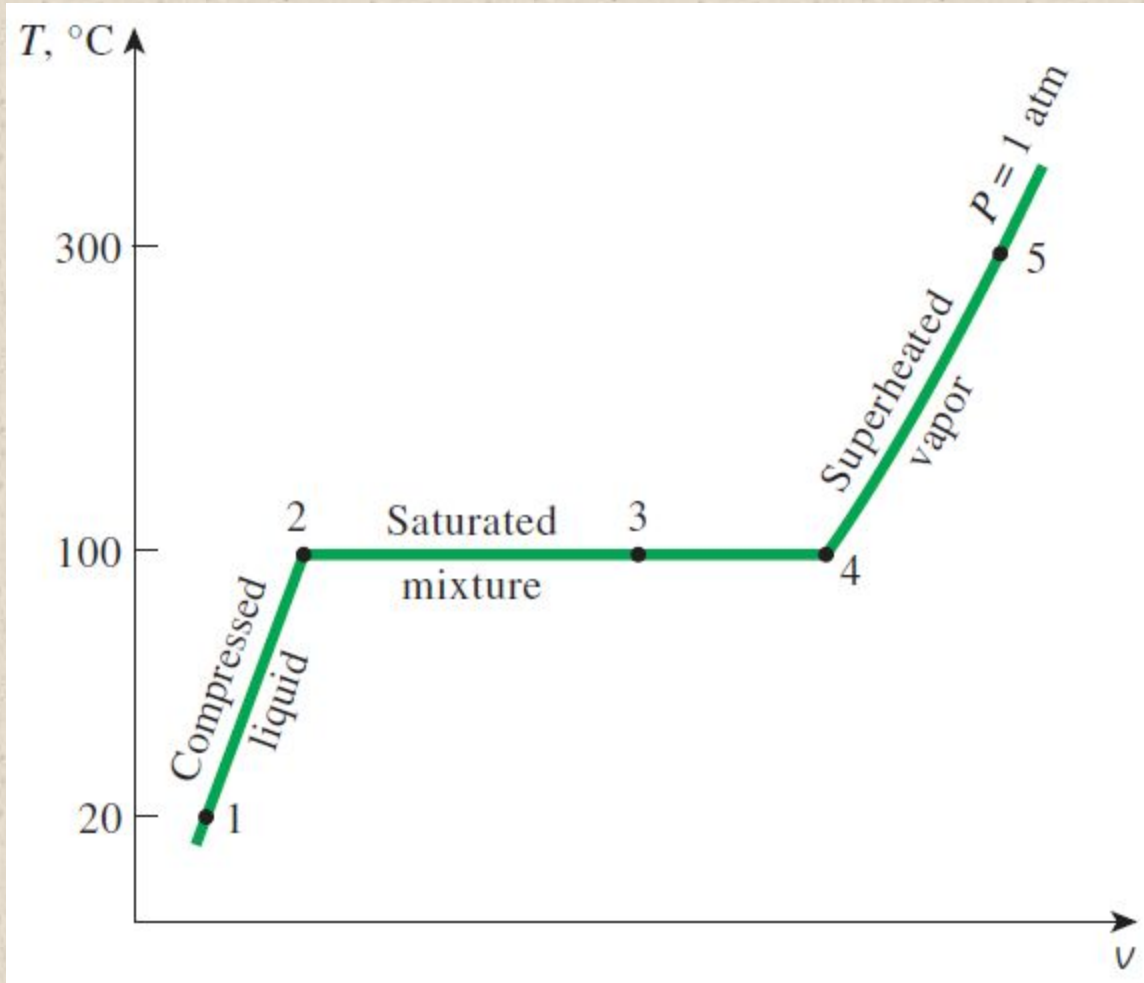
At 1 atm pressure, the temperature remains constant at  $100^\circ\text{C}$  until the last drop of liquid is vaporized (**saturated vapor**).



As more heat is transferred, the temperature of the vapor starts to rise (**superheated vapor**).



If the entire process between state 1 and 5 is reversed by cooling the water while maintaining the pressure at the same value, the water will go back to state 1, retracing the same path, and in so doing, the amount of heat released will exactly match the amount of heat added during the heating process.



*T-v diagram for the heating process of water at constant pressure.*

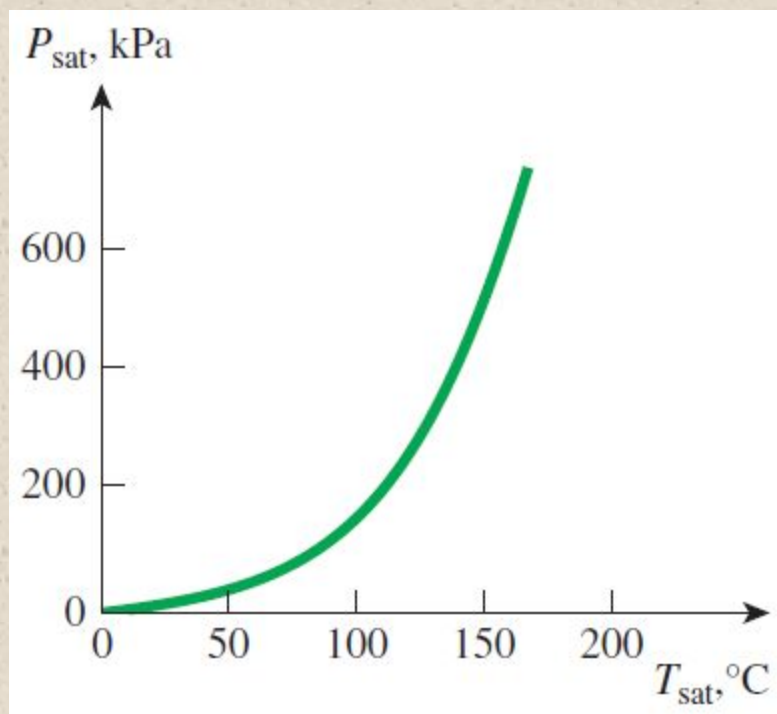
# Saturation Temperature and Saturation Pressure

The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.

*Water boils at 100°C at 1 atm pressure.*

**Saturation temperature  $T_{\text{sat}}$** : The temperature at which a pure substance changes phase at a given pressure.

**Saturation pressure  $P_{\text{sat}}$** : The pressure at which a pure substance changes phase at a given temperature.



The liquid–vapor saturation curve of a pure substance (numerical values are for water).

**TABLE 3–1**

Saturation (or vapor) pressure of water at various temperatures

Temperature $T, ^\circ\text{C}$	Saturation Pressure $P_{\text{sat}}, \text{kPa}$
–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



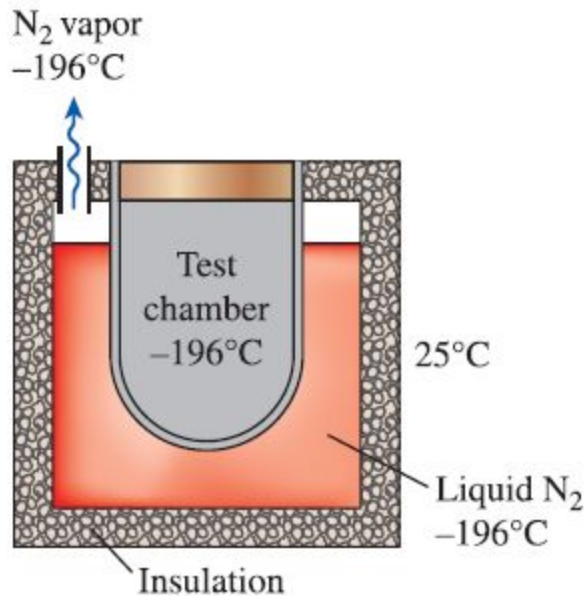
- **Latent heat:** The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion:** The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization:** The amount of energy absorbed during vaporization and it is equivalent to the energy released during condensation.
- The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs.
- At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.
- The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation.

**TABLE 3-2**

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

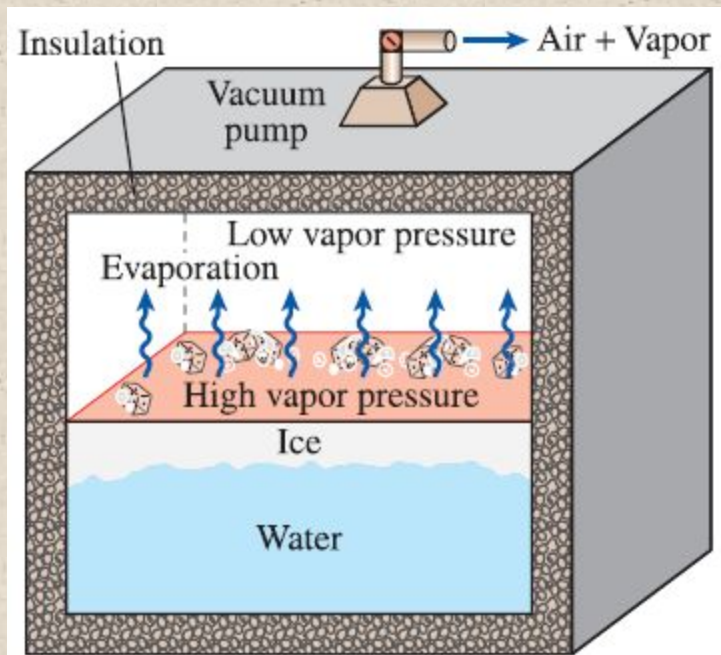
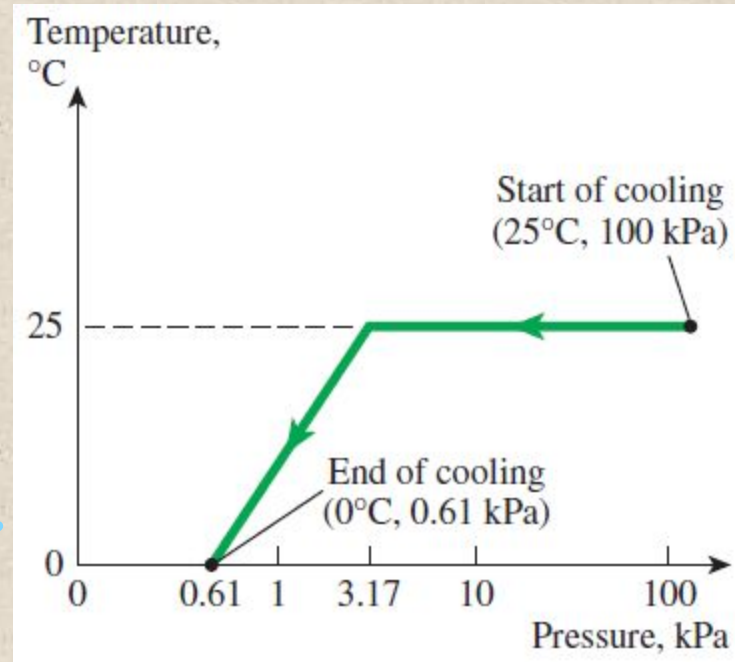
# Some Consequences of $T_{\text{sat}}$ and $P_{\text{sat}}$ Dependence



**FIGURE 3-12**

The temperature of liquid nitrogen exposed to the atmosphere remains constant at  $-196^{\circ}\text{C}$ , and thus it maintains the test chamber at  $-196^{\circ}\text{C}$ .

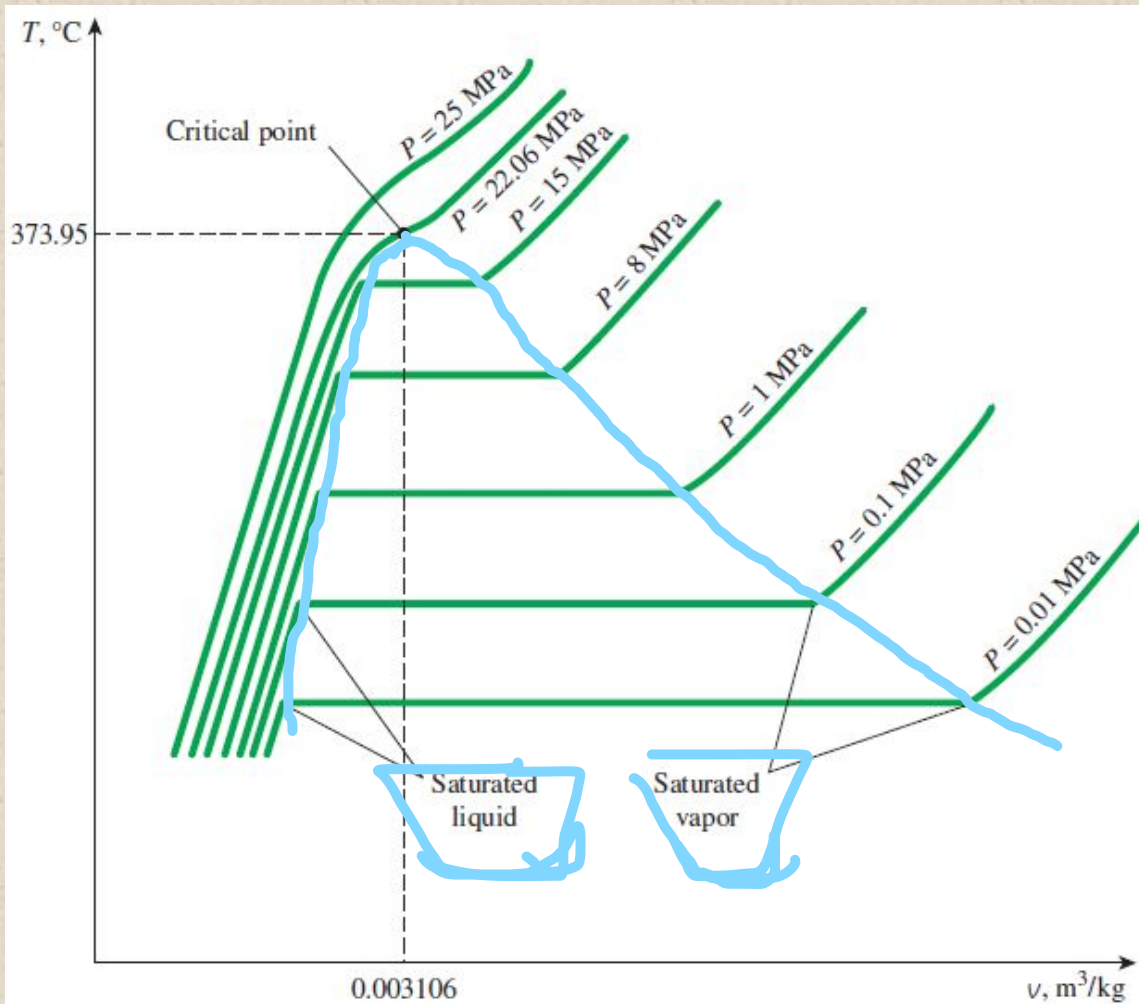
The variation of the temperature of fruits and vegetables with pressure during vacuum cooling from  $25^{\circ}\text{C}$  to  $0^{\circ}\text{C}$ .



In 1775, ice was made by evacuating the air space in a water tank.

# PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES

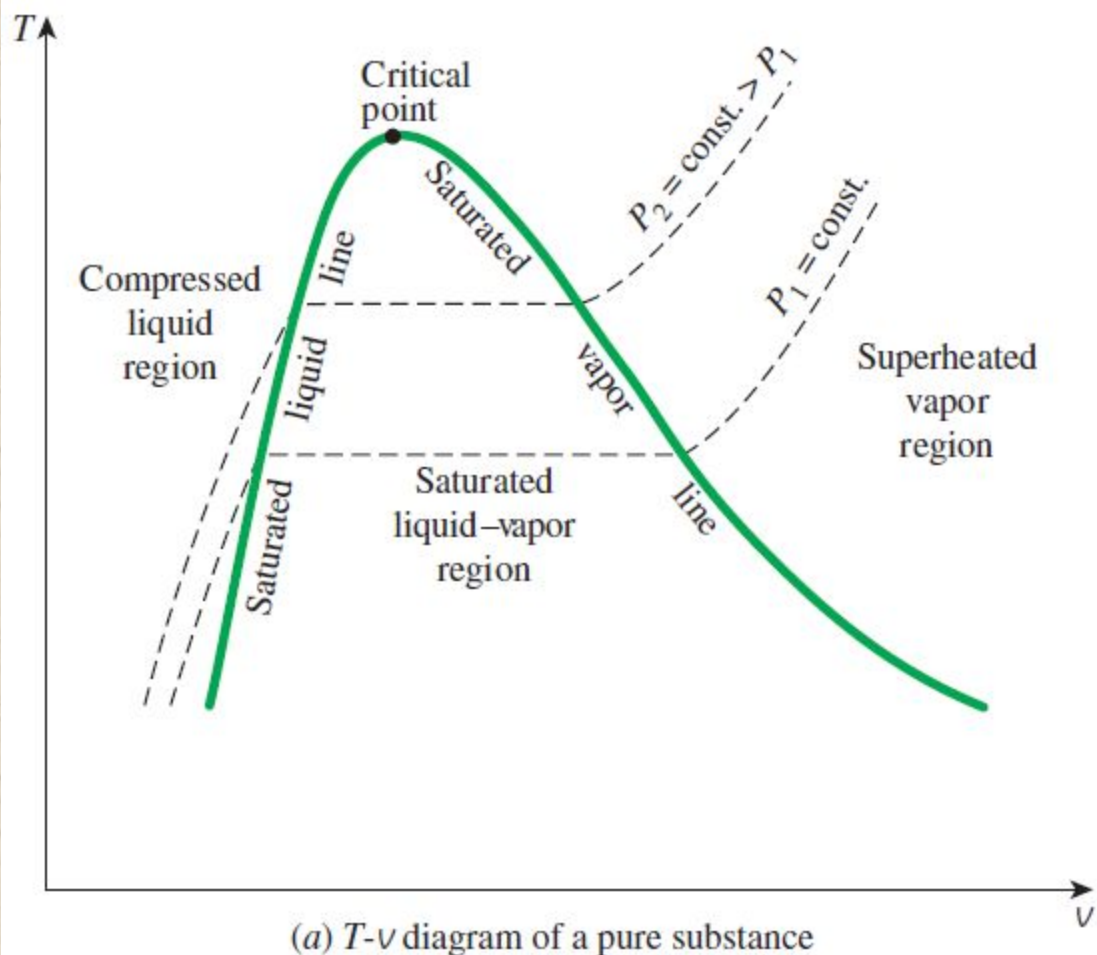
The variations of properties during phase-change processes are best studied and understood with the help of property diagrams such as the  $T$ - $v$ ,  $P$ - $v$ , and  $P$ - $T$  diagrams for pure substances.



$T$ - $v$  diagram of constant-pressure phase-change processes of a pure substance at various pressures (numerical values are for water).

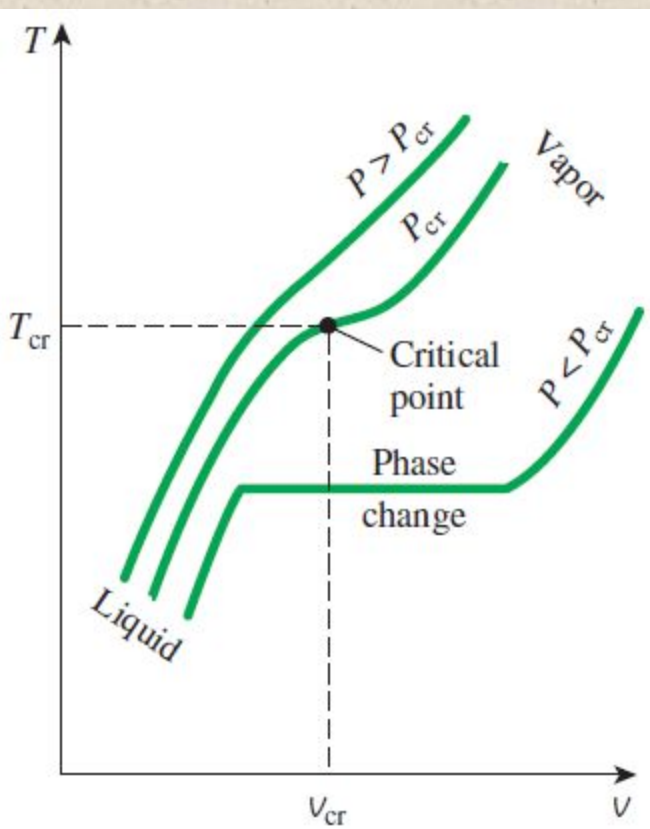


- saturated liquid line
- saturated vapor line
- compressed liquid region
- superheated vapor region
- saturated liquid–vapor mixture region (wet region)



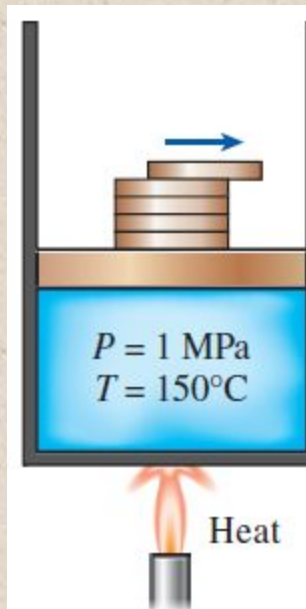
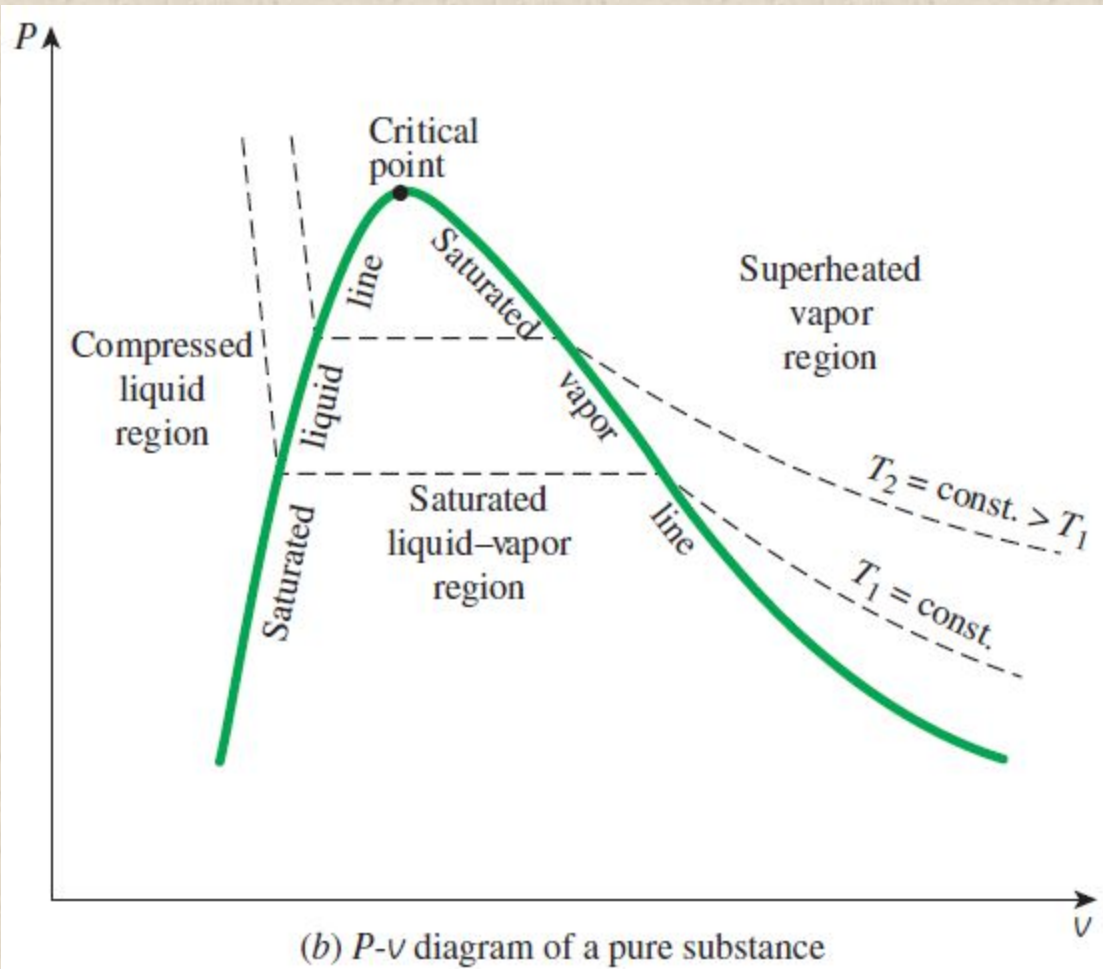
**FIGURE 3–17**

Property diagrams of a pure substance.



At supercritical pressures ( $P > P_{cr}$ ), there is no distinct phase-change (boiling) process.

**Critical point:** The point at which the saturated liquid and saturated vapor states are identical.



**FIGURE 3-18**

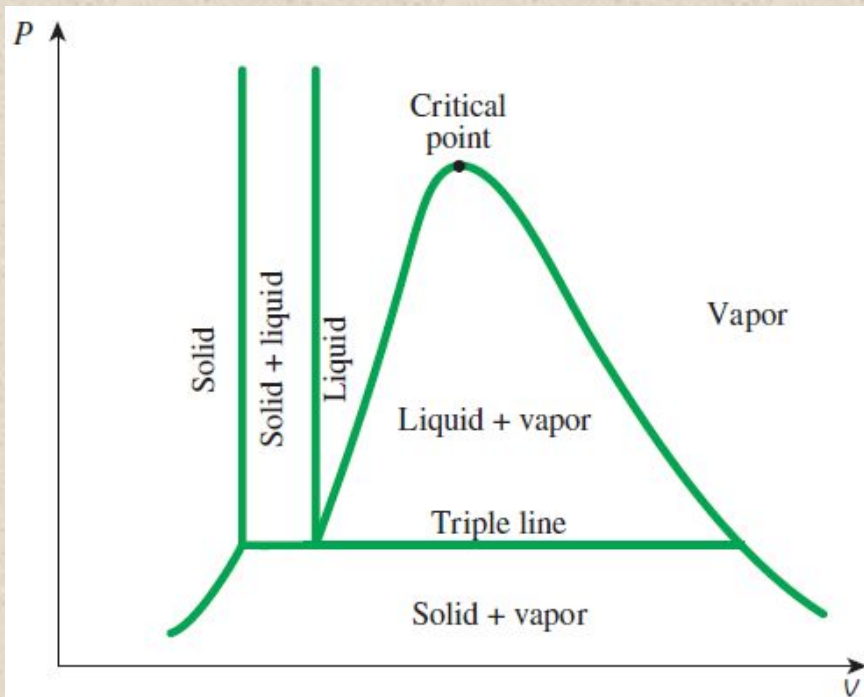
The pressure in a piston-cylinder device can be reduced by reducing the weight of the piston.

# Extending the Diagrams to Include the Solid Phase

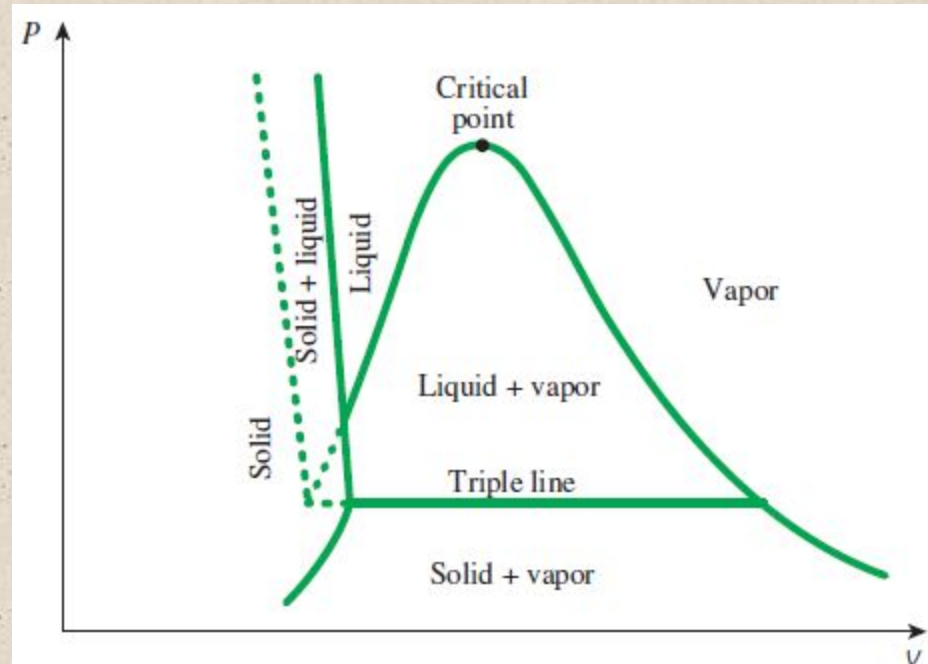
For water,  
 $T_{tp} = 0.01^\circ\text{C}$   
 $P_{tp} = 0.6117 \text{ kPa}$



At triple-point pressure and temperature, a substance exists in three phases in equilibrium.



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



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



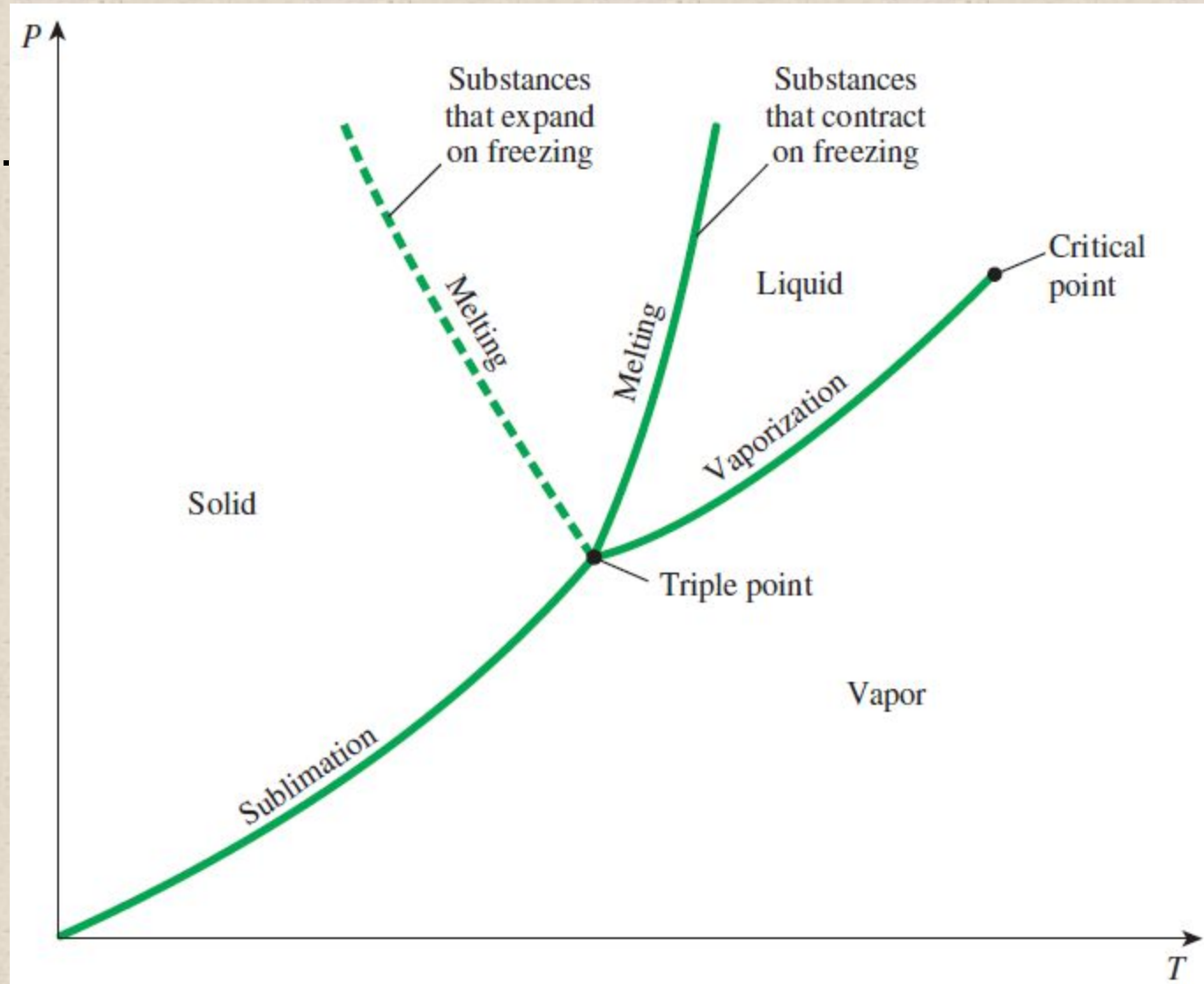
# Phase Diagram

## Sublimation:

Passing from the solid phase directly into the vapor phase.



At low pressures (below the triple-point value), solids evaporate without melting first (sublimation).



$P$ - $T$  diagram of pure substances.