# CAE 208 / MMAE 320: Thermodynamics

Fall 2023

## September 19, 2023

Properties of Pure Substances (I)

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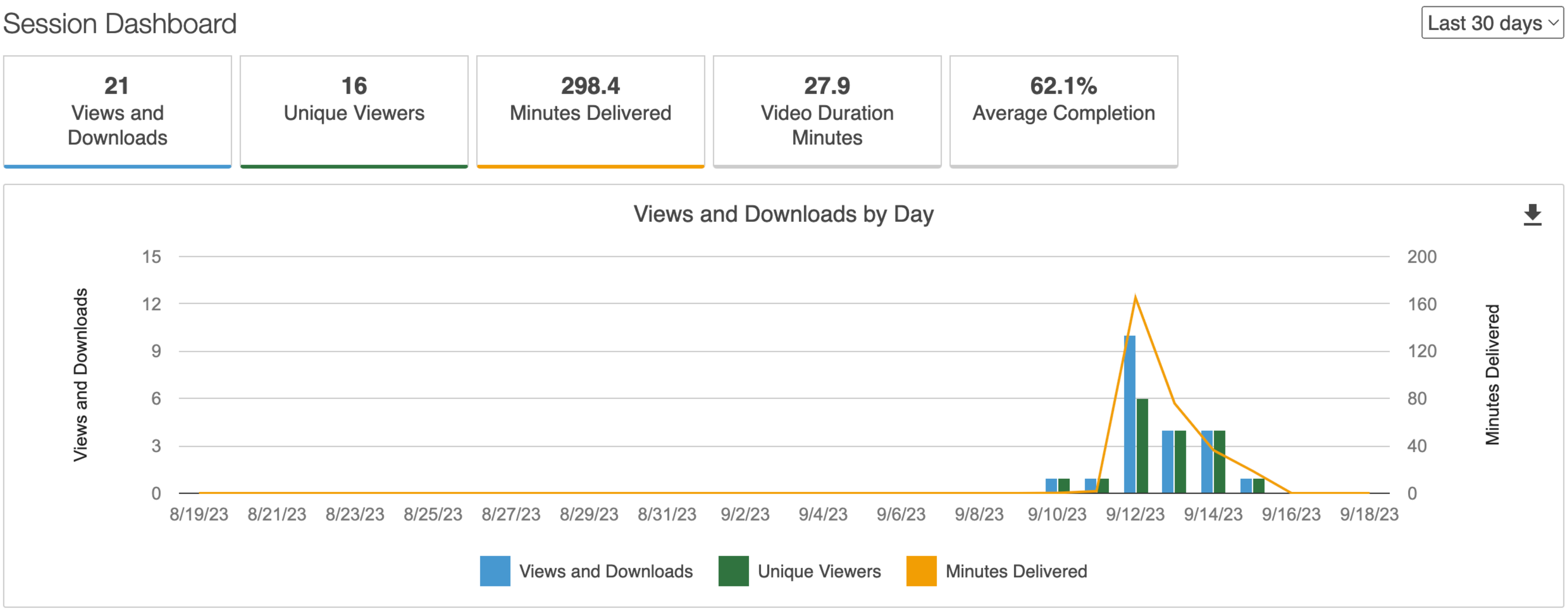
# ANNOUNCEMENTS

# Announcements

- Make sure to watch the recording materials:



# Announcements

- Assignment 3 is due this coming Thursday

# Announcements

- SI sessions are finalized:
  - ❑ Session 1: Monday 11:00 AM
  - ❑ Session 2: Thursday 11:00 AM
  - ❑ Session 3: Friday 11:00 AM
- The sessions are hybrid (zoom link was sent via Blackboard)

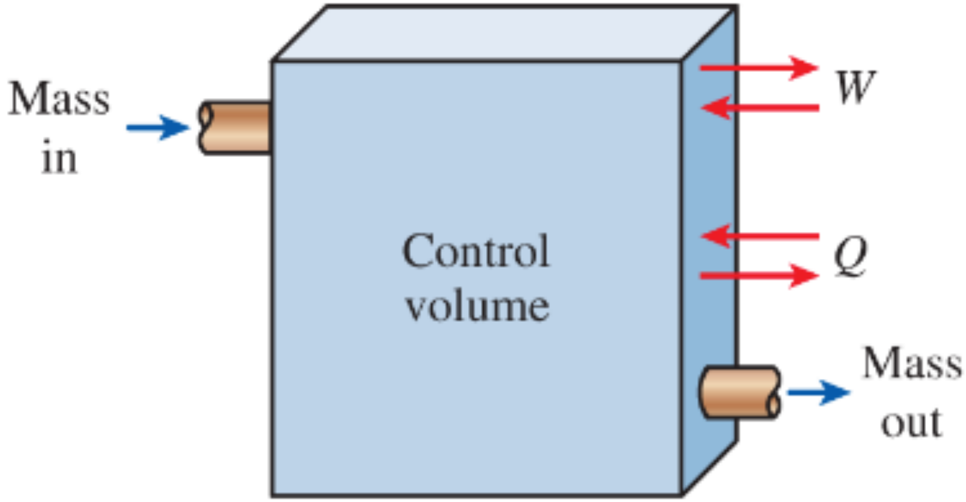
# Announcements

- Also, you have TA office hours:
  - Mondays 1 PM – 2:30 PM
  - Fridays 11:30 AM – 1 PM
- Or schedule an appointment:
  - Saman Haratian
  - Office: Alumni Memorial Hall Room 217
  - Email: sharatian@hawk.iit.edu

# RECAP

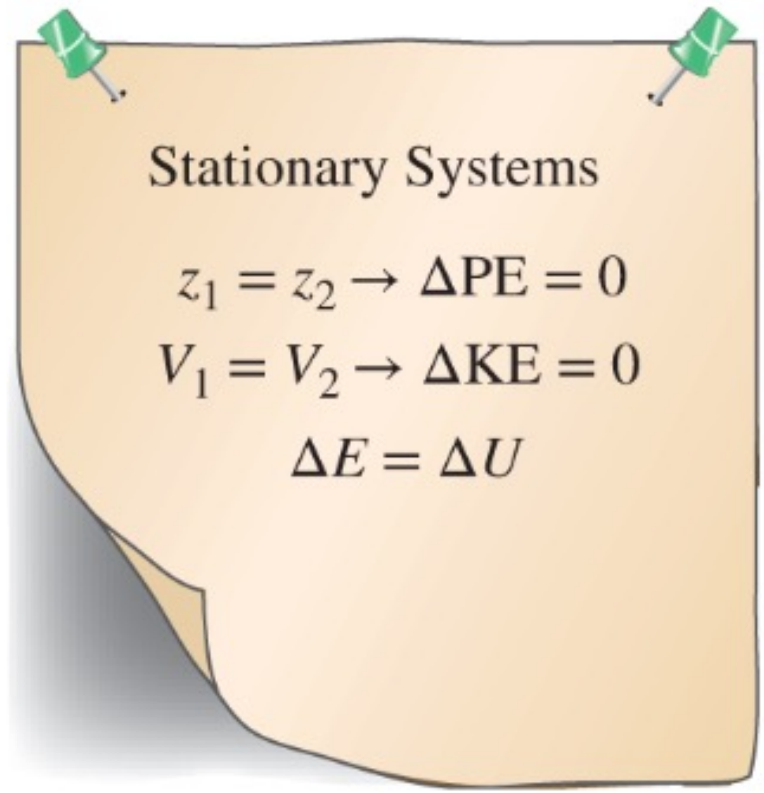
# Recap

- 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

- Most systems encountered in practice are stationary:



# Recap

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

Change in internal, kinetic, potential, …, energies

Net energy transfer by heat, work, and mass

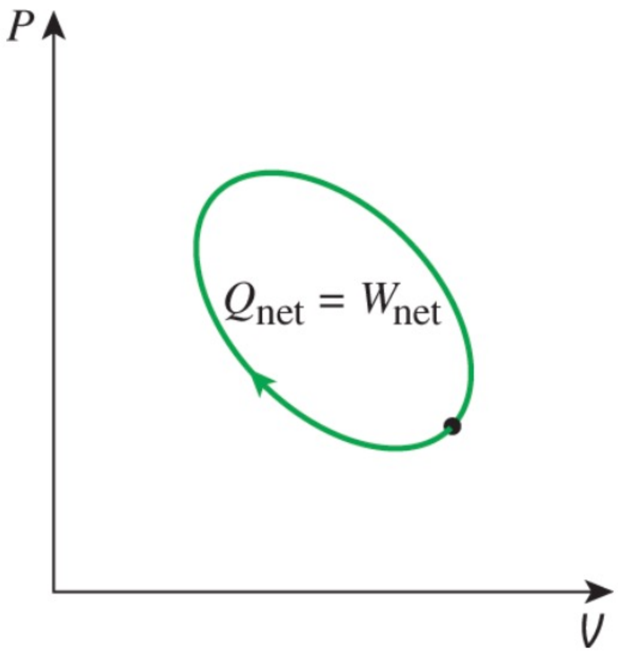
$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + \left(E_{mass,in} - E_{mass,out}\right) = \Delta E_{system}$$

# Recap

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

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

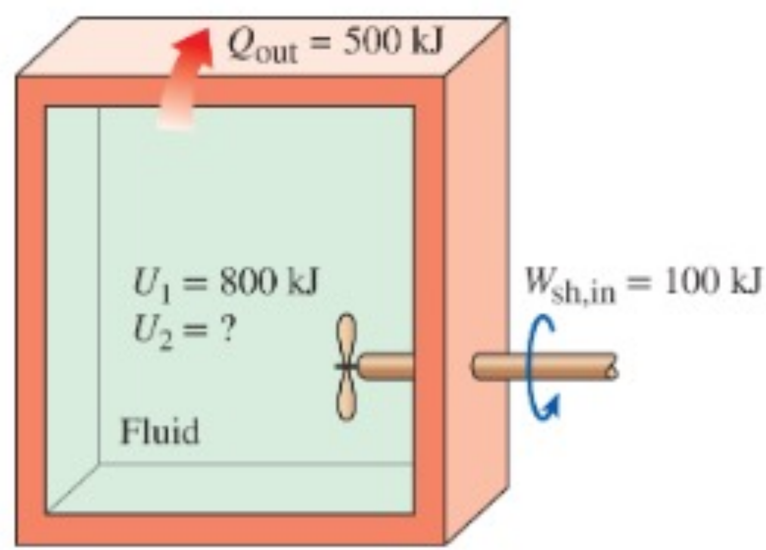
$$W_{net,out} = Q_{net,in} \quad \rightarrow \dot{W}_{net,out} = \dot{Q}_{net,in}$$



# CLASS ACTIVITY

# Class Activity

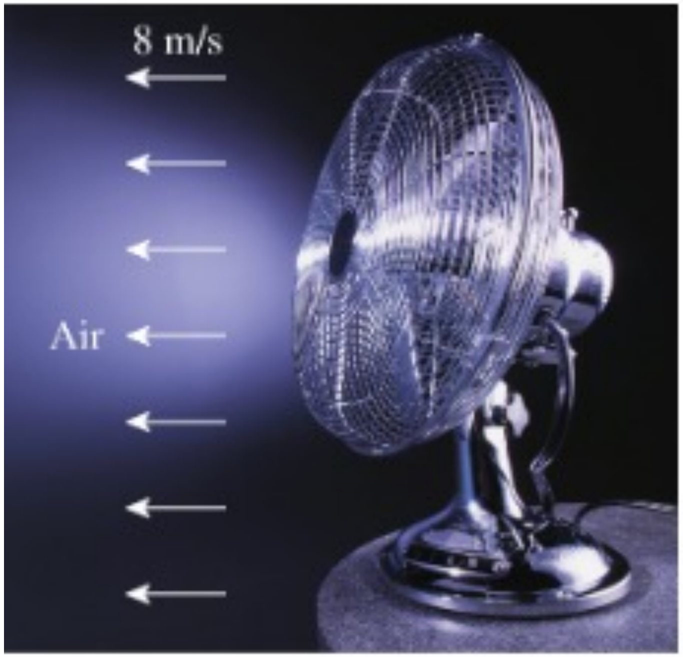
- A rigid tank contains a hot flid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel



# CLASS ACTIVITY

# Class Activity

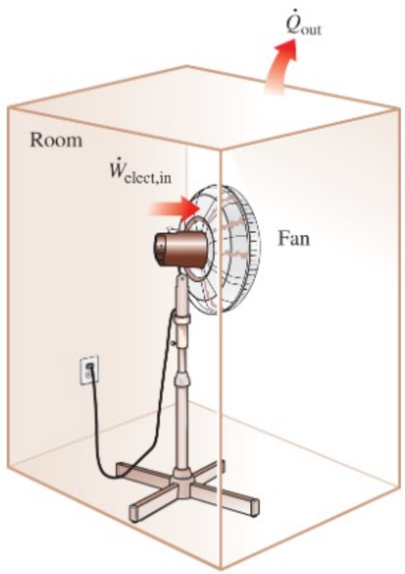
- A fan that consumes 20 W of electric power when operating is claimed to discharge air from a ventilated room at a rate of 1 kg/s at a discharge velocity of 8 m/s. Determine if this claim is reasonable



# CLASS ACTIVITY

# Class Activity

- A room is initially at the outdoor temperature of 25 °C. Now a large fan that consumes 200 W of electricity when running is turned on The heat transfer rate between the room and the outdoor air is given $\dot{Q} = UA(T_i - T_o)$ where U = 6 W/m$^2$C is the overall heat transfer coefficient. A = 30 m$^2$ is the exposed surface area of the room, $T_i$ and $T_o$ are the indoor and outdoor air temperatures, respectively. Determine the indoor air temperature when steady operating are established



# ENERGY CONVERSION EFFICIENCIES

# Energy Conversion Efficiencies

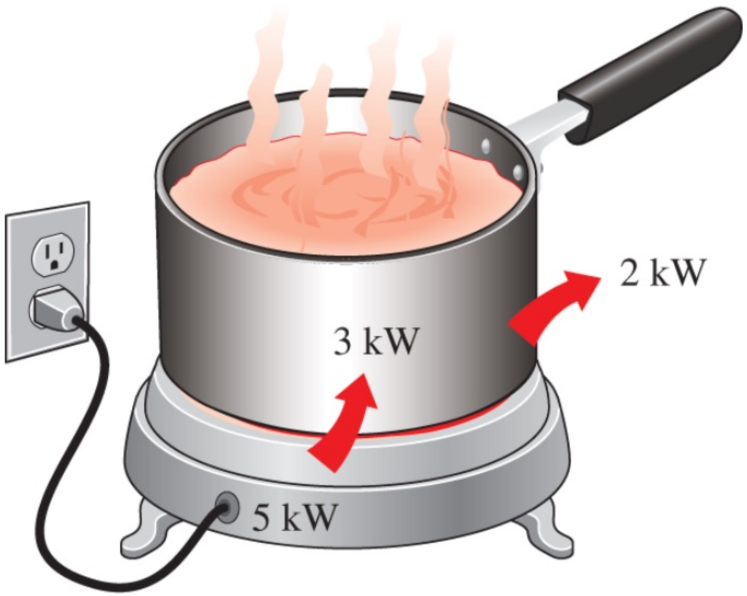
- Efficiency, in general, can be expressed in terms of the desired output and the required input as:

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

# Energy Conversion Efficiencies

- Efficiency of a cooking appliance

$$Efficiency = \frac{Energy\ Utilized}{Energy\ supplied\ to\ appliace}$$



# Energy Conversion Efficiencies

- Summarize efficiencies:

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

# Energy Conversion Efficiencies

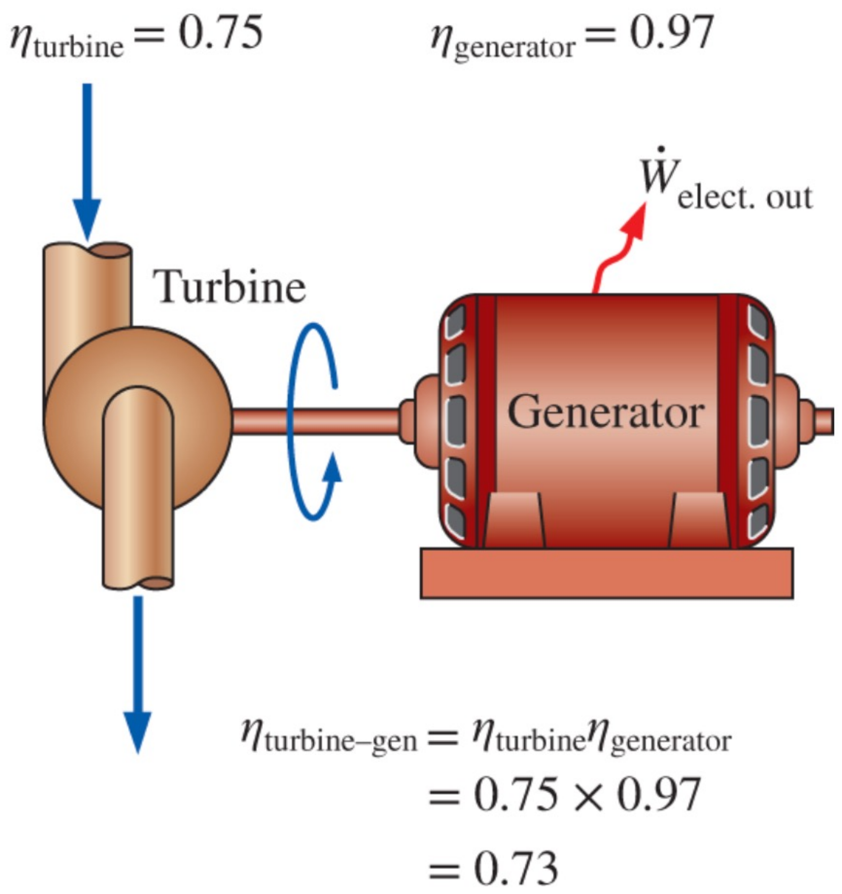
- Summarize efficiencies:

$$\eta_{pump} = \frac{mechanical\ energy\ increase\ of\ the\ fluid}{Mechanical\ energy\ input} = \frac{E_{mech,fluid}}{\dot{W}_{shaft,in}} = \frac{\dot{W}_{pump,u}}{\dot{W}_{pump}}$$

$$\eta_{turbine} = \frac{mechanical\ energy\ output}{Mechanical\ energy\ decrease\ of\ the\ fluid} = \frac{\dot{W}_{shaft,out}}{|\Delta\dot{E}_{mech,fluid}|} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine,e}}$$

# Energy Conversion Efficiencies

- Summarize efficiencies:



# CLASS ACTIVITY

# Class Activity

- Can the combined pump–motor efficiency be greater than either the pump or the motor efficiency?

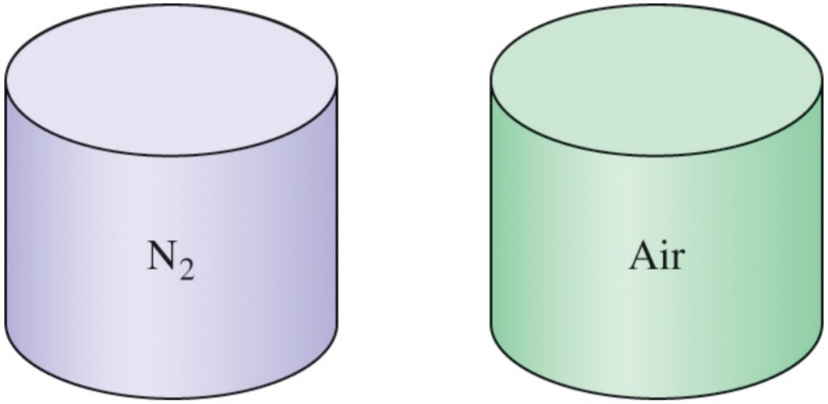
# QUIZ

# Quiz

# PURE SUBSTANCE

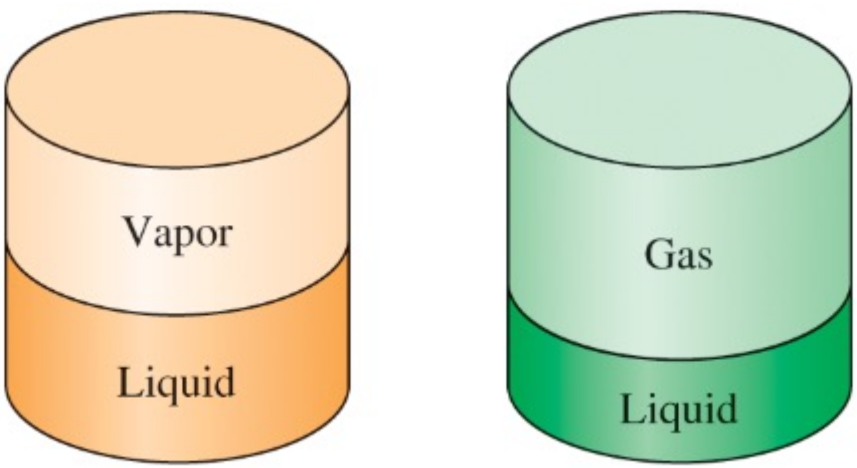
# Pure Substance

- *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)

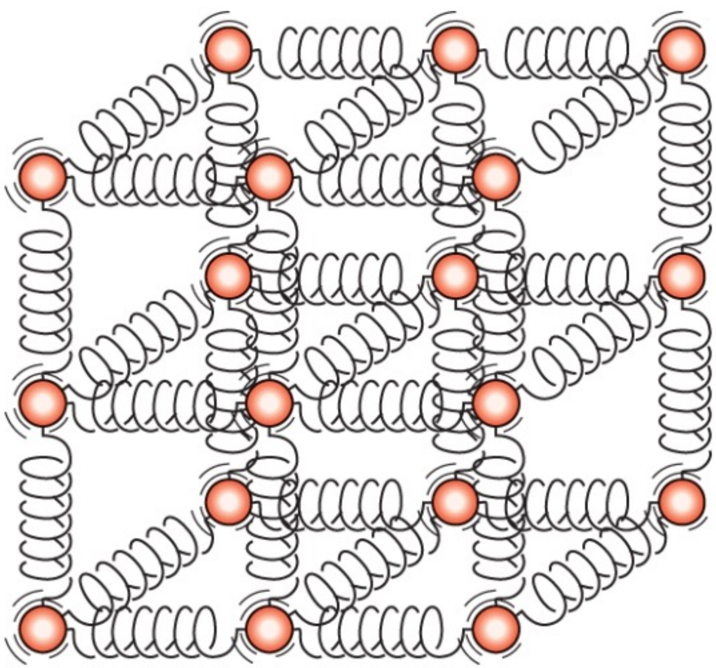
- A phase is identified as having distinct molecular arrangement that is homogenous throughout and separated from others by easily identifiable boundary surfaces (e.g., $H_2O$)

# 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

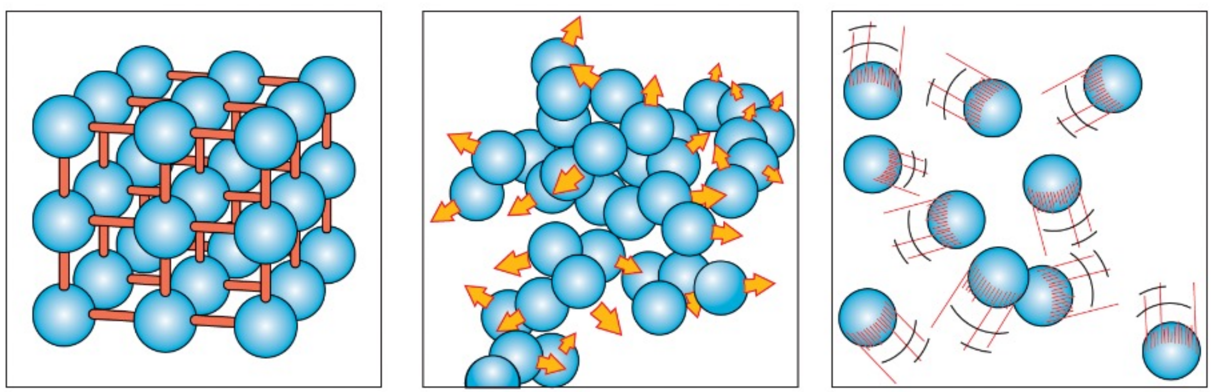


# Phases of a Pure Substance

- 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

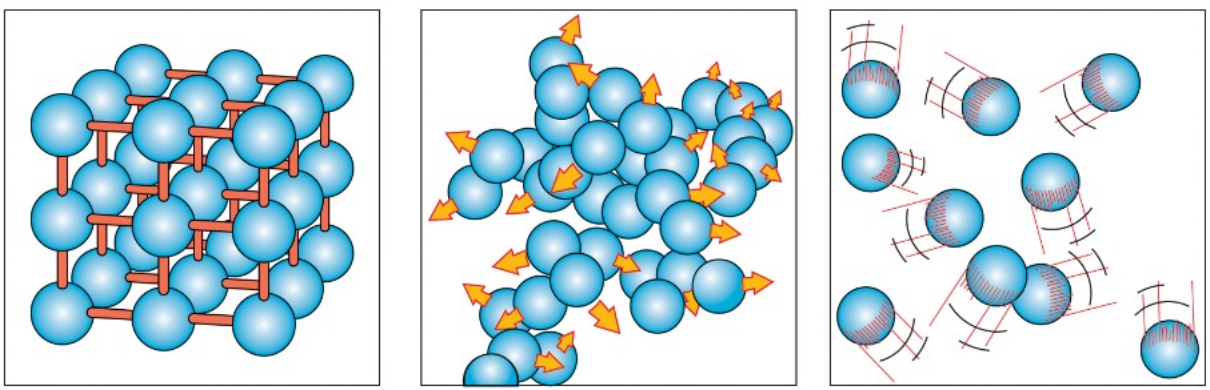
- Liquid:
  - ❑ Molecular sparing is not much different from that of the solid phase except the molecules are no longer at fixed positions relative to each other and they can rotate and translate freely
  - ❑ Intermolecular forces are weaker relative to solids but still relatively strong compared to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



(a) (b) (c)

# Phases of a Pure Substance

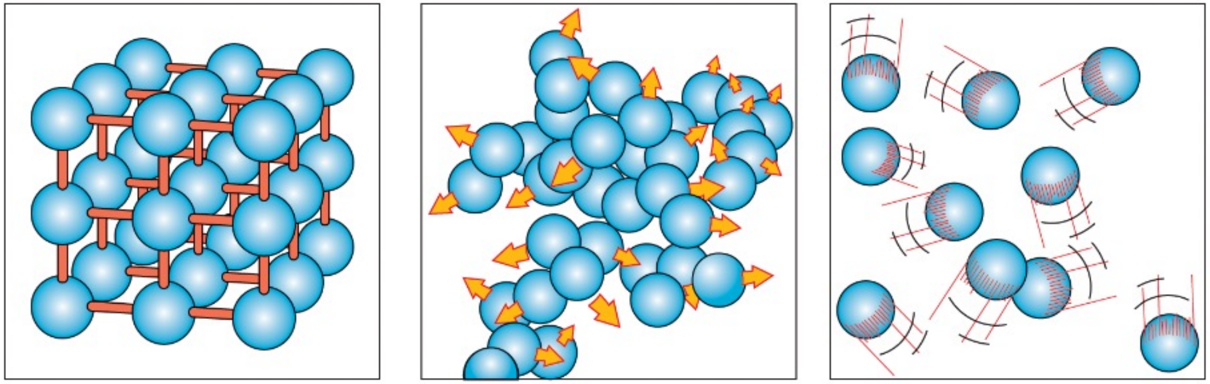
- Gas:
  - ❑ Molecules spacing are far apart from each other and molecular order is nonexistent
  - ❑ Gas molecules move about a random continually colliding with each other and the walls of the container they are in
  - ❑ At low densities, the intermolecular forces are very small, and collisions are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



(a) (b) (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

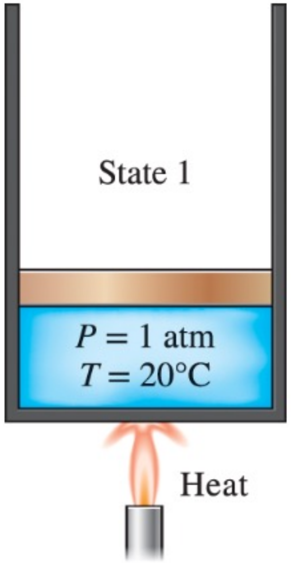
- There are many practical situations where two phases of a pure substance co-exist in equilibrium

  - ❑ 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

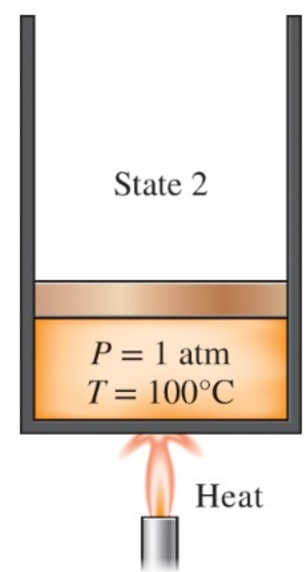
# Phase Change Processes of Pure Substances

- 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)

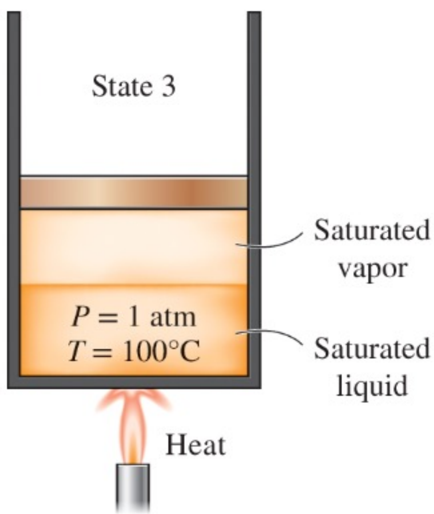


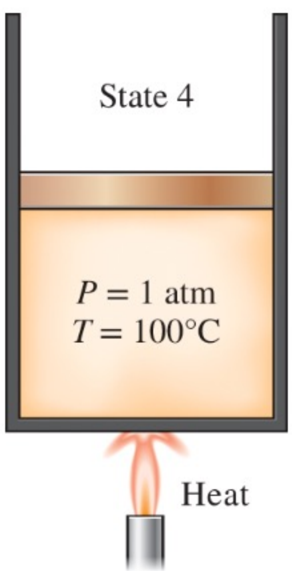
# Phase Change Processes of Pure Substances

- 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)

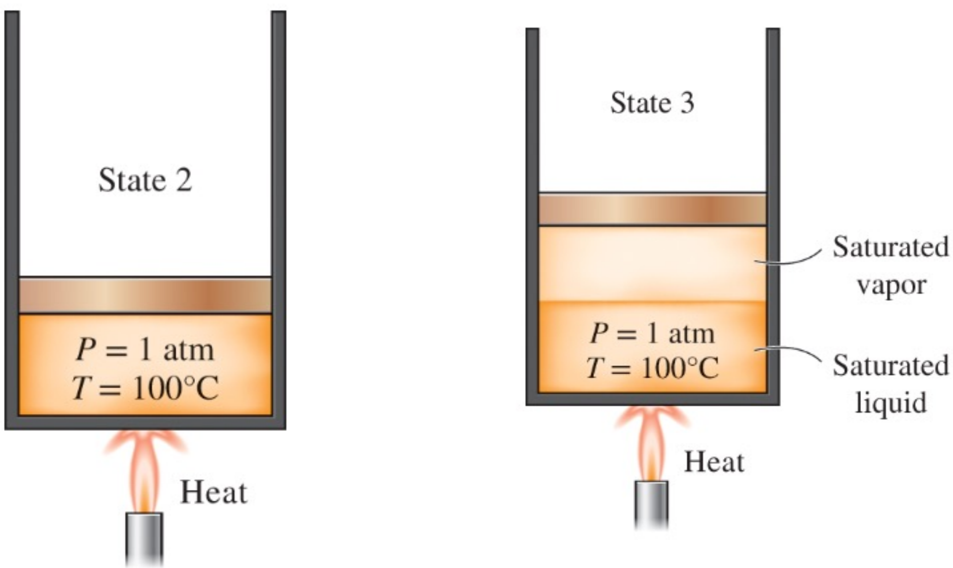
  - ❑ A vapor that is about to condensate is called a saturated vapor



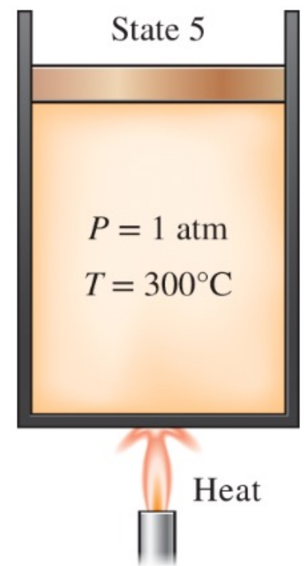
# Phase Change Processes of Pure Substances

- Saturated liquid-vapor mixture



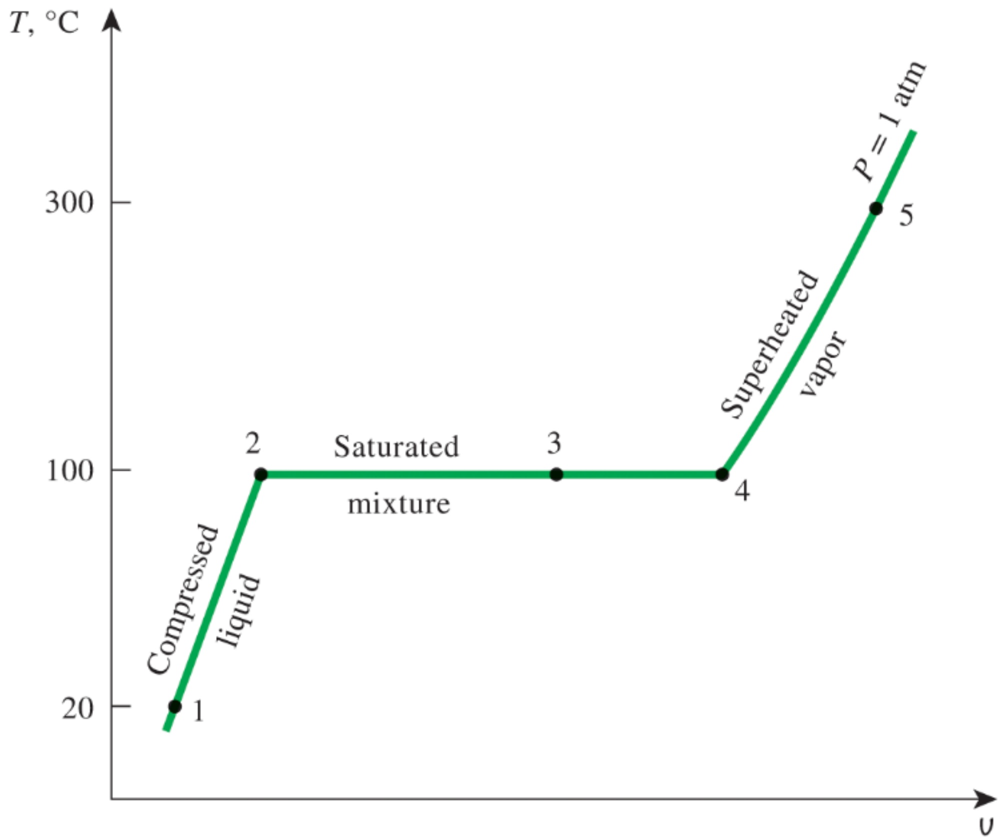
# Phase Change Processes of Pure Substances

- 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

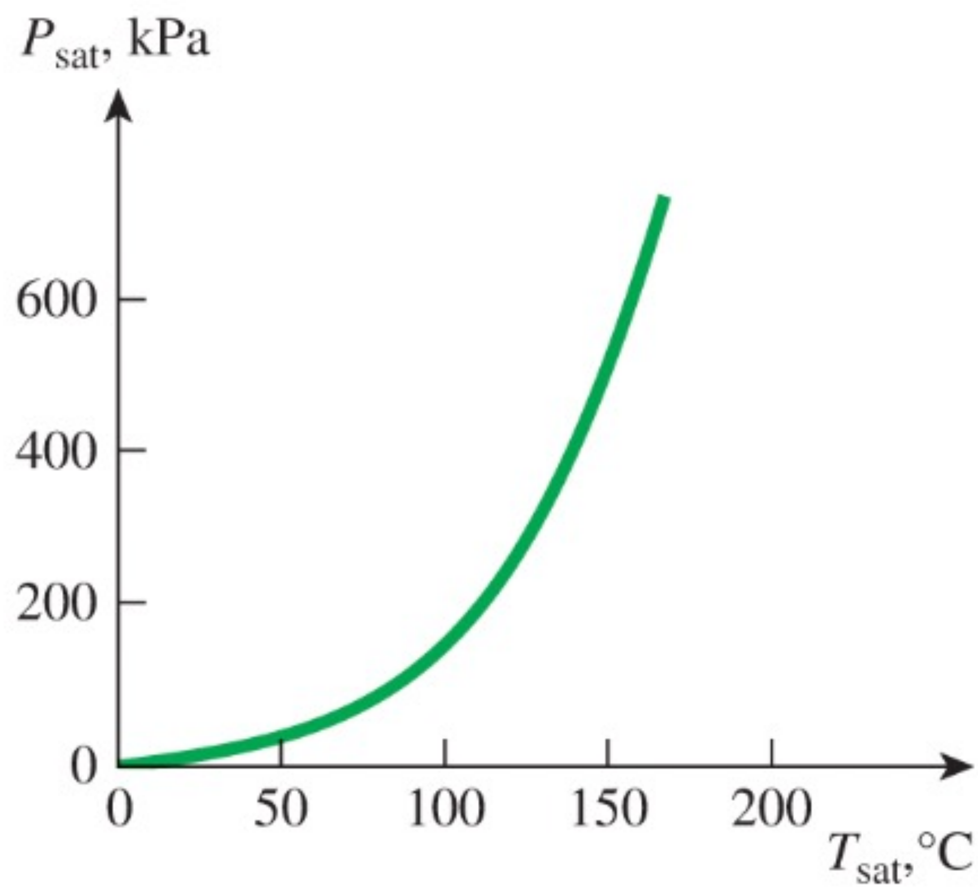
- It takes a large amount of energy to melt a solid or vaporize a liquid. The amount of energy absorbed or released during a phase-change process is called the *latent heat*

  - 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**

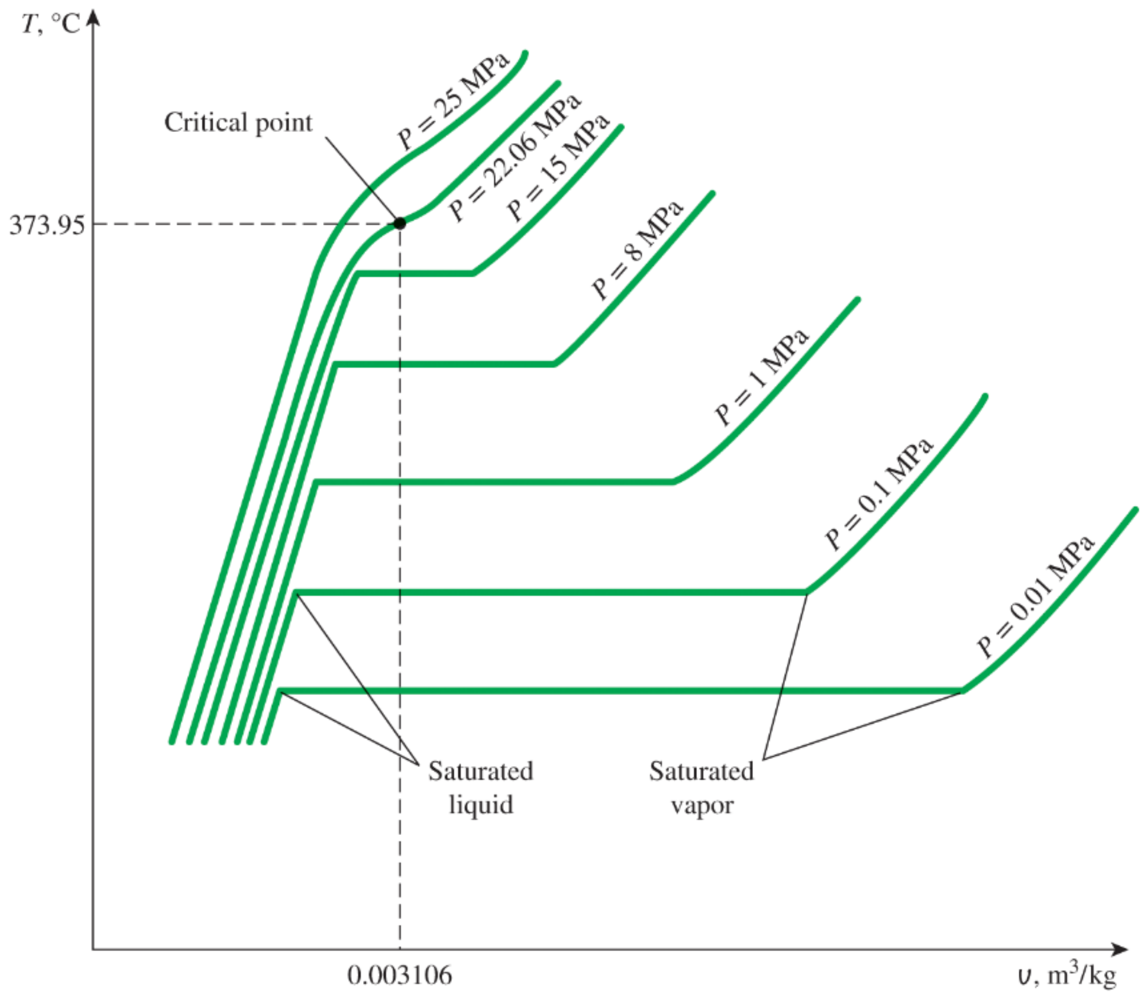
**Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude**

| 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) | $v_{cr}$ ($m^3/kg$) |
|---|---|---|---|
| Water | 22.06 | 373.95 | 0.003106 |
| Helium | 0.23 | -267.85 | 0.01444 |

# Property Diagrams For Phase-Change Processes

- Table A-1

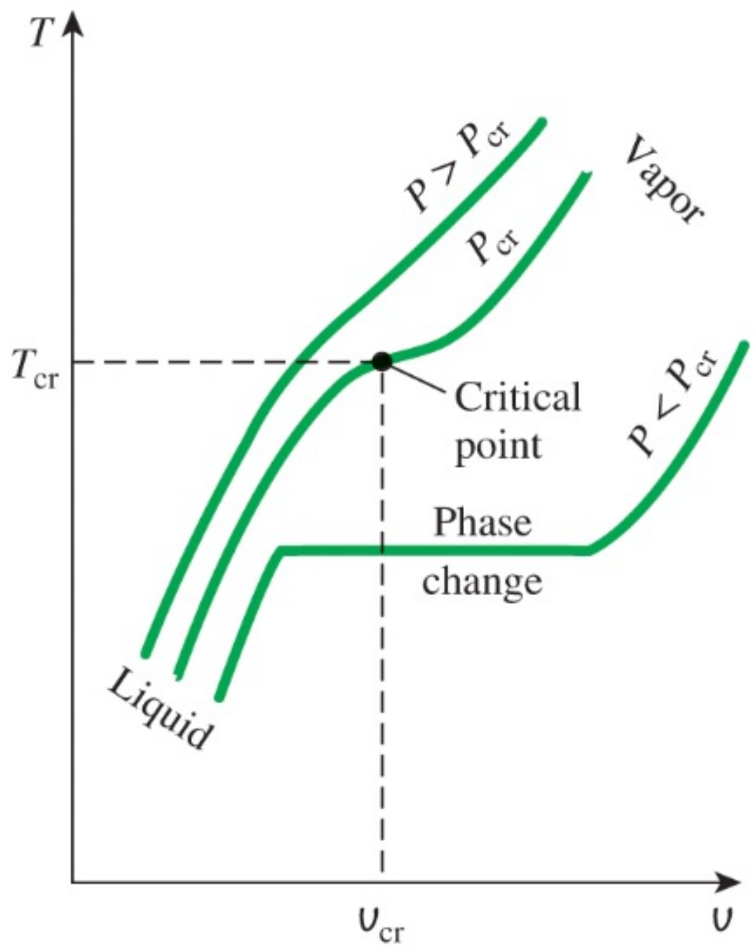
**TABLE A–1**

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 | $C_6H_6$ | 78.115 | 0.1064 | 562 | 4.92 | 0.2603 |
| Bromine | $Br_2$ | 159.808 | 0.0520 | 584 | 10.34 | 0.1355 |

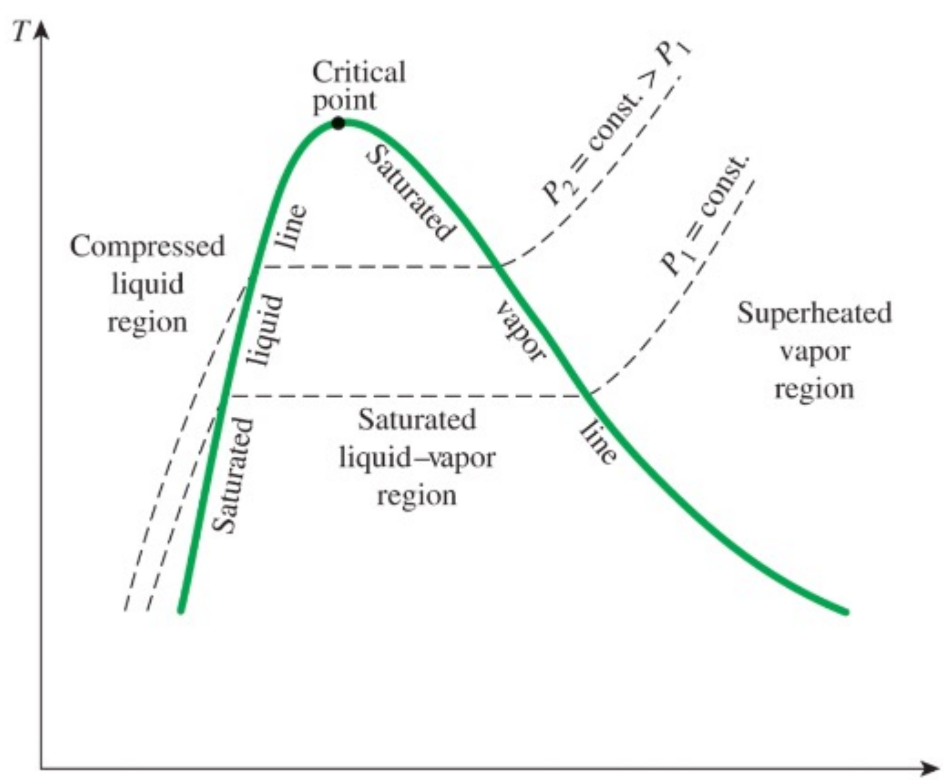
# Property Diagrams For Phase-Change Processes

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



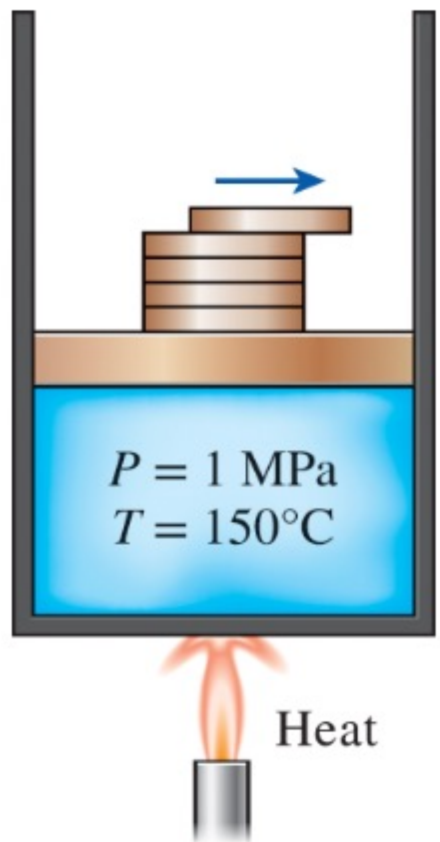
# Property Diagrams For Phase-Change Processes

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



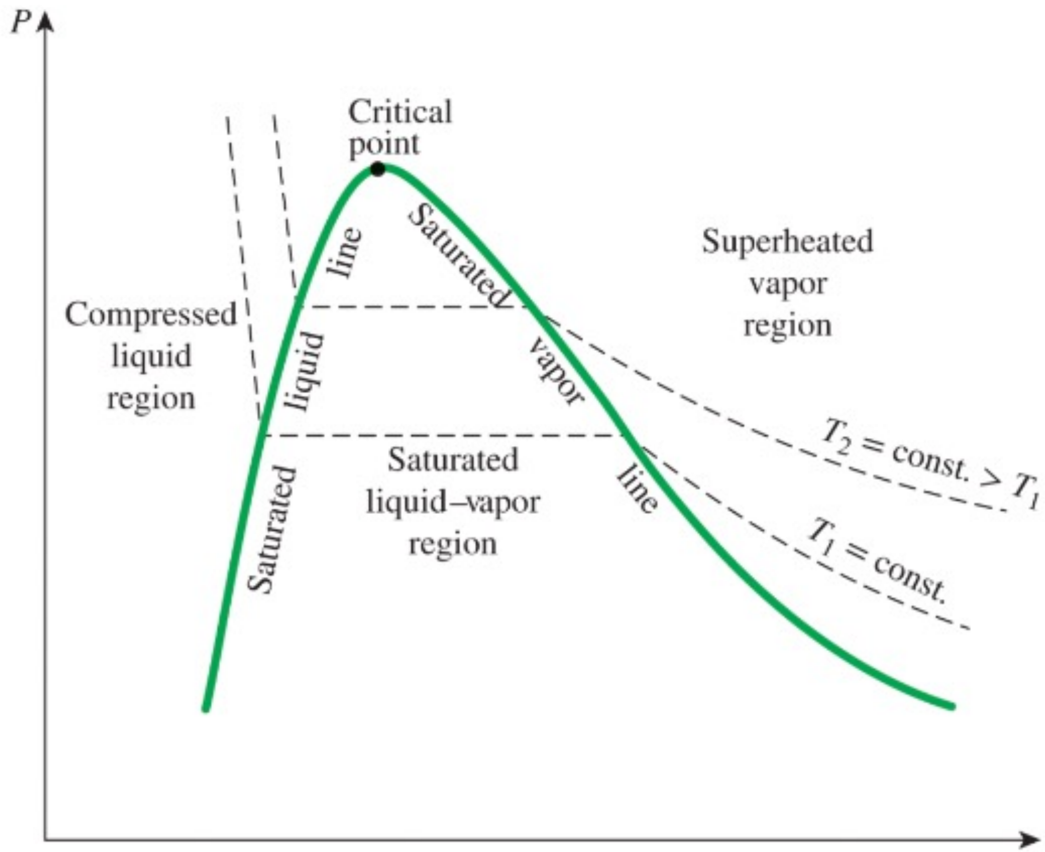
# Property Diagrams For Phase-Change Processes

- Repeat the experiment to get the P-v diagram



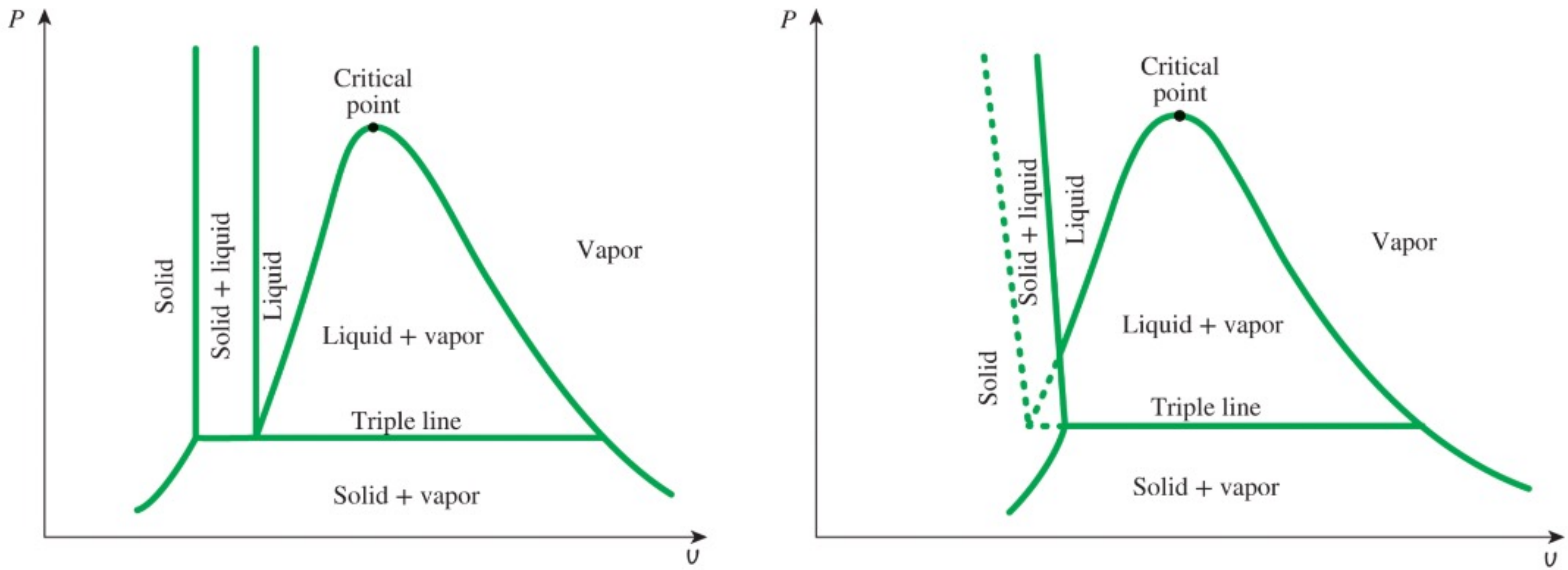
# Property Diagrams For Phase-Change Processes

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



# Property Diagrams For Phase-Change Processes

- Extending the diagram to include solid phase:




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

(*b*) *P*-υ 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**

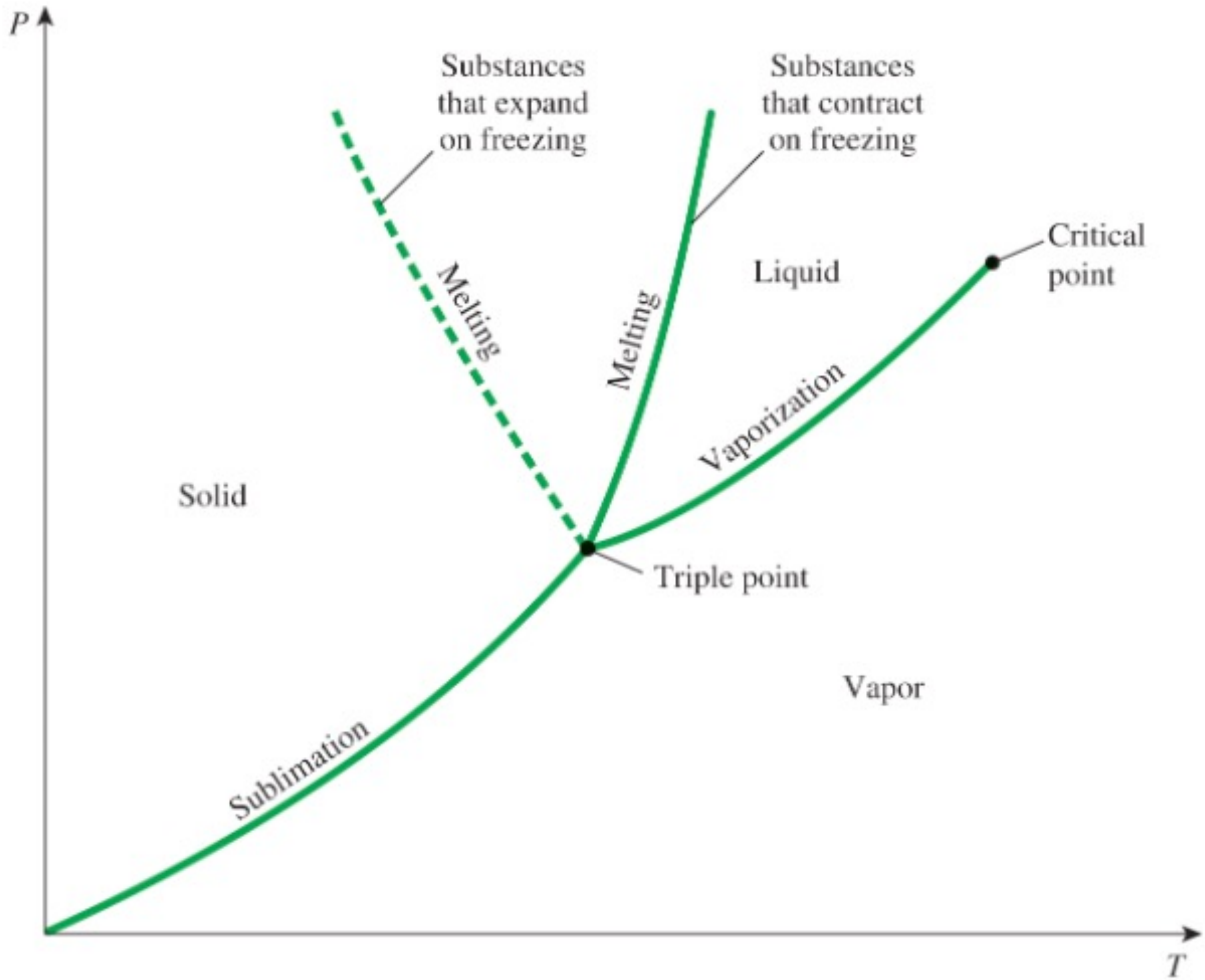
| Substance | Formula | $T_{tp}$, K | $P_{tp}$, kPa |
|---|---|---|---|
| Acetylene | $C_2H_2$ | 192.4 | 120 |
| Ammonia | $NH_3$ | 195.40 | 6.076 |
| Argon | A | 83.81 | 68.9 |
| Carbon (graphite) | C | 3900 | 10,100 |
| Carbon dioxide | $CO_2$ | 216.55 | 517 |
| Carbon monoxide | CO | 68.10 | 15.37 |
| Deuterium | $D_2$ | 18.63 | 17.1 |
| Ethane | $C_2H_6$ | 89.89 | $8 \times 10^{-4}$ |
| Ethylene | $C_2H_4$ | 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 | $1.65 \times 10^{-7}$ |
| Water | $H_2O$ | 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)

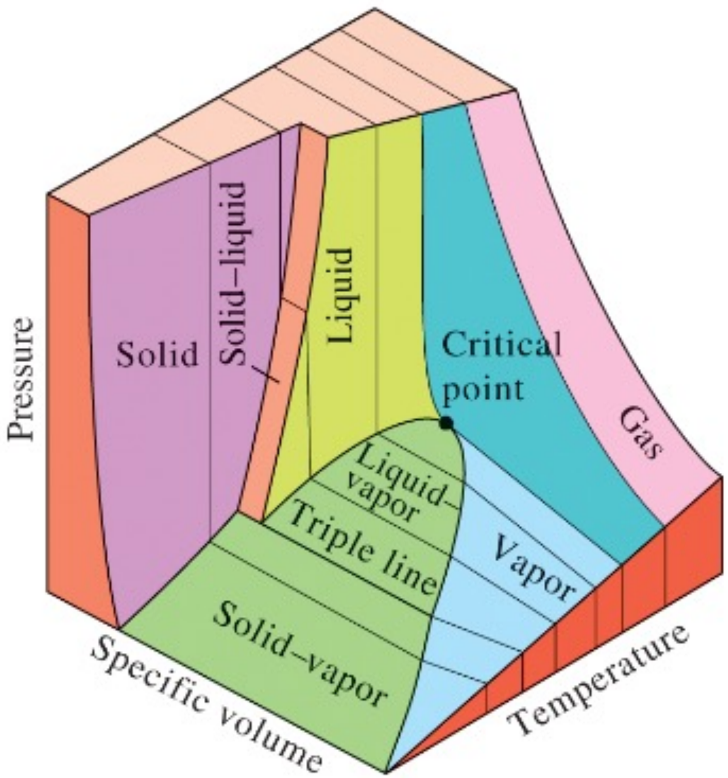
# Property Diagrams For Phase-Change Processes

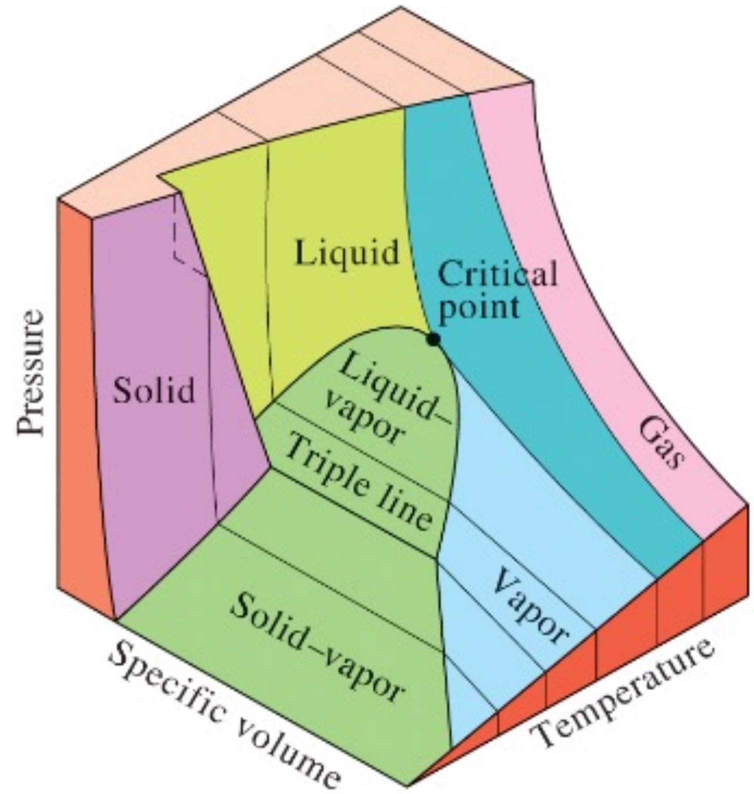
- P-T diagram is known as the phase diagram



# 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 $CO_2$?