

Chapter 3

Fluid Mechanics

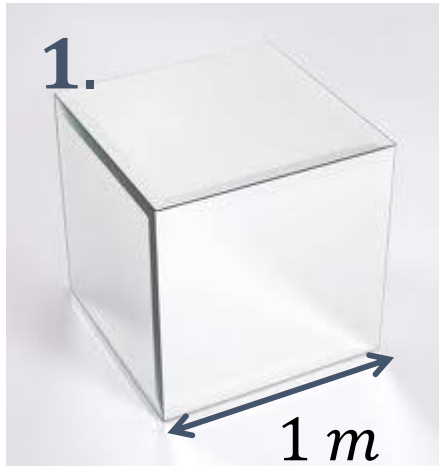
- Density and Pressure in Static Fluid
- Buoyant Forces, Archimedes' Principle
- Moving Fluids and Bernoulli's Equation
- Properties of Bulk Matter, stress and Strain



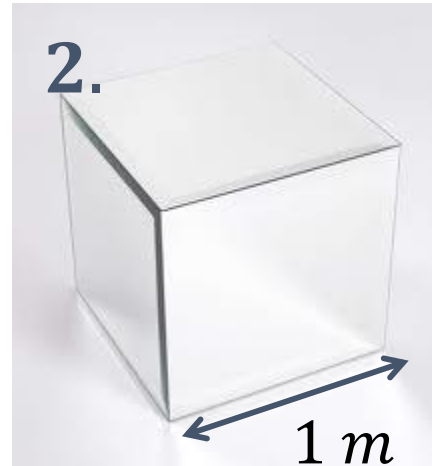
Density, specific weight, specific gravity

- **Density, ρ** (decreases with rise in T)
 - mass per unit volume (kg/m^3)
 - for water density = 1000 kg/m^3
 - **Specific Weight, γ** (Heaviness of fluid)
 - weight per unit volume $\gamma = \rho g$
 - for water $\gamma = 9.81 \text{ kN/m}^3$
 - **Specific Gravity = SG**
 - Ratio of the density of a fluid to the density of water
- $SG = \rho_f / \rho_w$ SG of Hg = 13.55

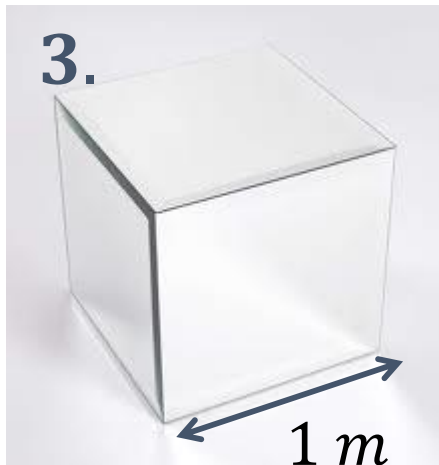
The cubic vessels contain the water at different temperatures. Which water has the **highest** density?



1 kg of
water at
 73°C



1 kg of
water at
 273°C



1 kg of
water at
 273°K



1 kg of
water at
 373°C

Example

A object has a mass of 36 grams and the volume of the water (reference material) is 3 mL. Find (a) the density, (b) the specific weight and (c) the specific gravity of the object. Also, specify if the object will sink or float in the water? The density of the water is 1 g/mL.

Solution:

(a) Density of object:

$$\rho = m/v = 36g/3mL = 12 \text{ g/mL} = 12 \text{ kg/L}$$

(b) Specific weight:

$$\gamma = \rho g = 12 \text{ kg/L} \times 9.81 \text{ m/s}^2 = 117.72 \text{ N/mL}$$

(C) Specific Gravity:

$$SG = \rho_{liquid} / \rho_{H_2O} = \frac{12g/mL}{1g/mL} = 12$$

The specific gravity is greater than 1 so the object will sink in the water.

What is a Fluid?

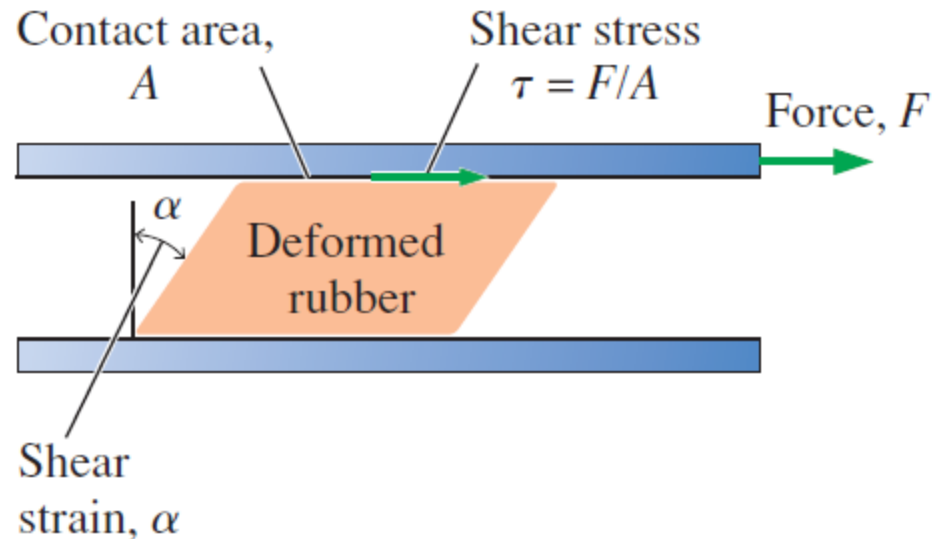
A fluid is a substance that deforms continuously under the influence of a shear stress, no matter how small.

Fluids exist in a **liquid** or **gas phase**.

In solids, stress is proportional to *strain*, e.g., Hooke's law

In fluids, stress is proportional to *strain rate*.

When a constant shear force is applied, a solid eventually stops deforming at some fixed strain angle, whereas a fluid never stops deforming and approaches a constant *rate* of strain.



Stress and Strain

Stress: Force per unit area.

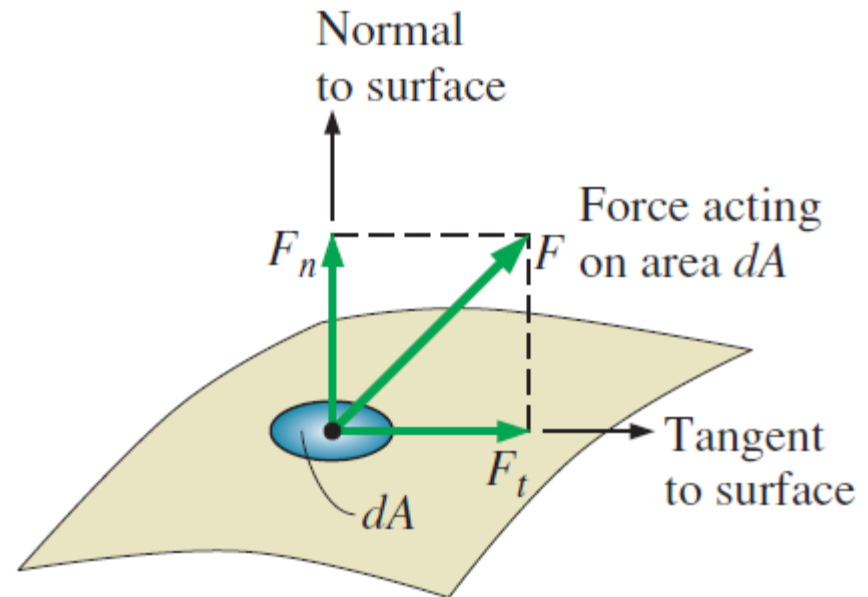
Normal stress: The normal component of a force acting on a surface per unit area.

Shear stress: The tangential component of a force acting on a surface per unit area.

Pressure: The normal stress in a fluid at rest.

Zero shear stress: A fluid at rest is at a state of zero shear stress.

When the walls are removed or a liquid container is tilted, a shear develops as the liquid moves to re-establish a horizontal free surface.



$$\text{Normal stress: } \sigma = \frac{F_n}{dA}$$

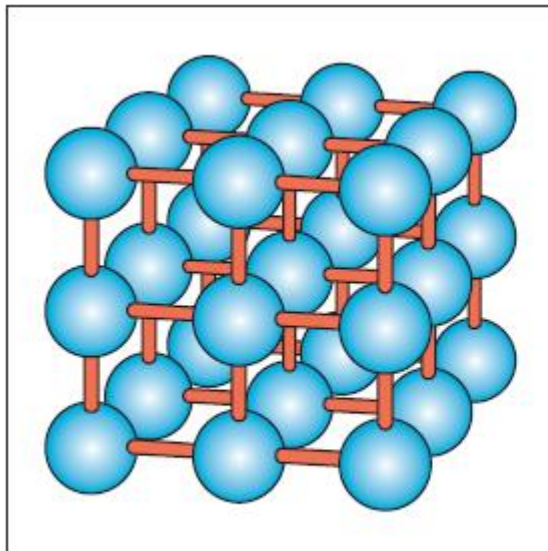
$$\text{Shear stress: } \tau = \frac{F_t}{dA}$$

Intermolecular bonds are strongest in solids and weakest in gases.

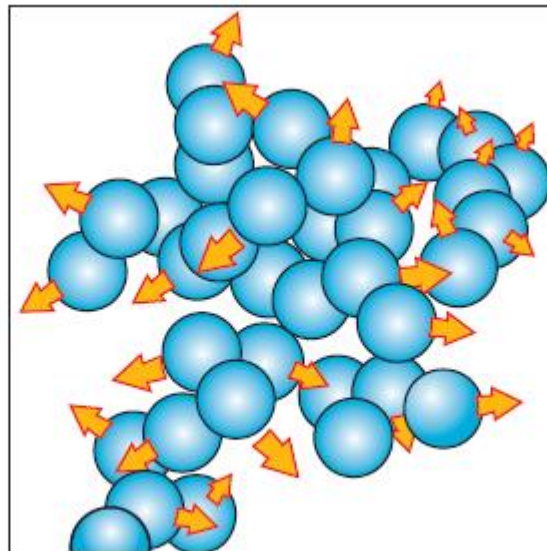
Solid: molecules are at relatively fixed positions in some pattern

Liquid: molecules rotate and translate relative to each other

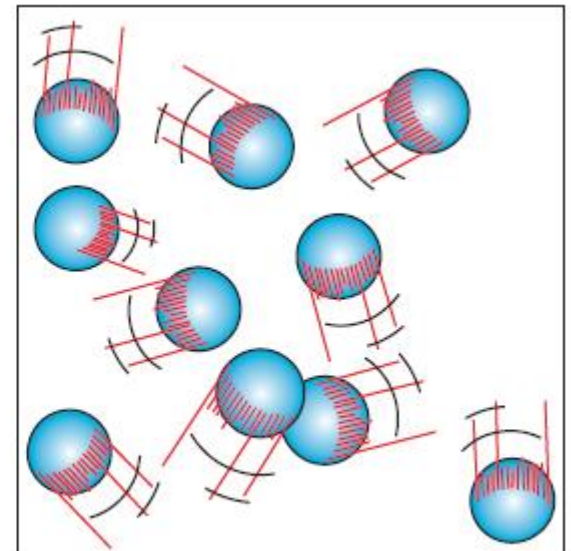
Gas: molecules are far apart from each other and move randomly



(a)



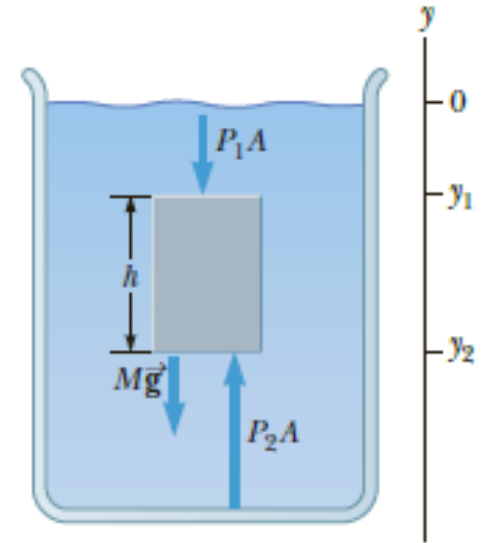
(b)



(c)

Pressure

- If an object is immersed in a fluid, the fluid exerts a force on every part of the object's surface.
- If the object and fluid are at **rest**, the force is perpendicular to the element of area on which it acts.



- The **pressure is the force per unit area**, measured in N/m², called Pascals

$$\left. \begin{aligned} P_2A - P_1A - Mg &= 0 \\ M &= \rho V = \rho A(y_2 - y_1) \end{aligned} \right\}$$

$$P_2 = P_1 + \rho g(y_2 - y_1)$$

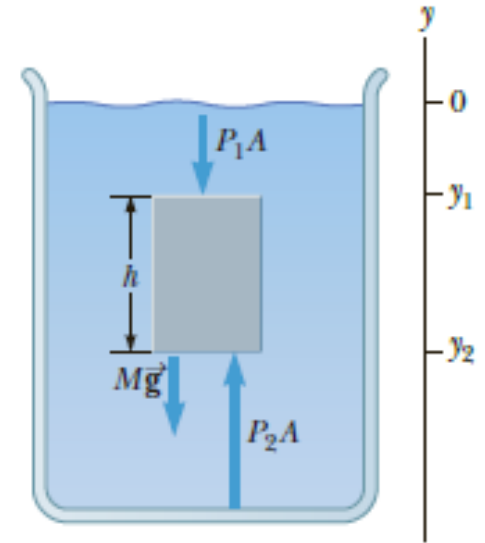
Pressure

- Let $y_1 = 0$ be the free surface of the liquid
- At the free surface the pressure is atmospheric pressure P_0 :

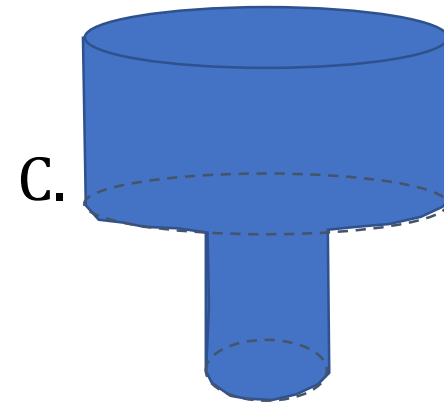
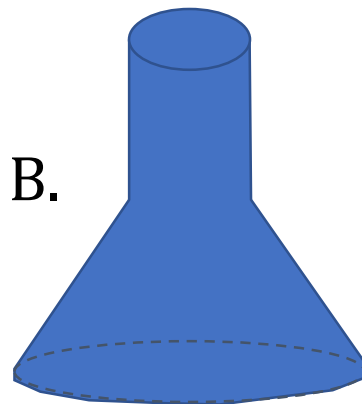
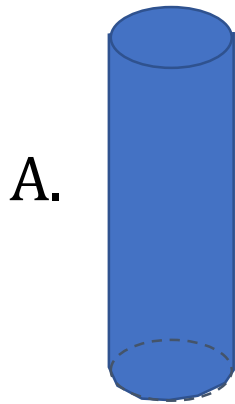
$$P_0 = 1.013 \times 10^5 \text{ Pa at sea level}$$

- Then, the pressure at any depth h will be

$$P = P_0 + \rho gh$$

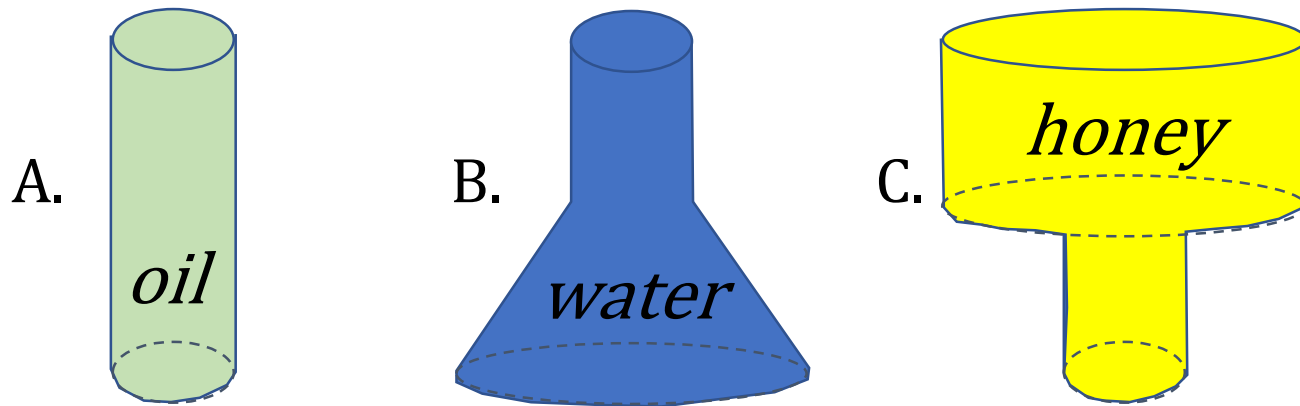


Consider the three open containers filled with water.
How do the pressures at the bottoms compare ?



1. $P_A = P_B = P_C$
2. $P_A < P_B = P_C$
3. $P_A < P_B < P_C$
4. $P_B < P_A < P_C$
5. Not enough information

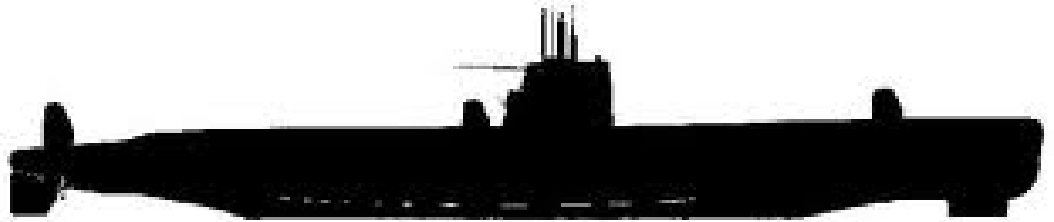
The three open containers are now filled with oil, water and honey respectively. How do the pressures at the bottoms compare ?



1. $P_A = P_B = P_C$
2. $P_A < P_B = P_C$
3. $P_A < P_B < P_C$
4. $P_B < P_A < P_C$
5. Not enough information

Calculating Crush Depth of a Submarine

A nuclear submarine is rated to withstand a pressure difference of 70 atm before catastrophic failure. If the internal air pressure is maintained at 1 atm , what is the maximum permissible depth?



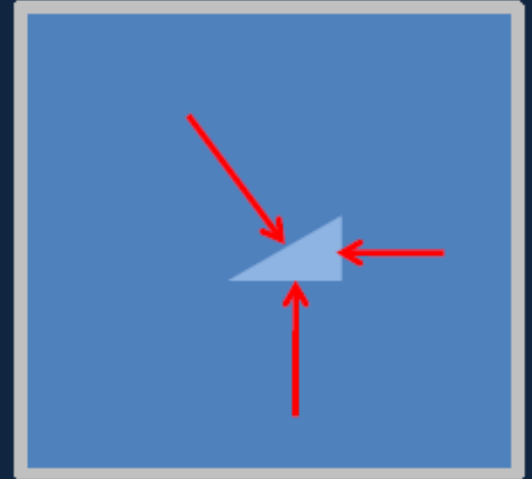
$$P = P_0 + \rho gh$$

$$P - P_0 = 70 \text{ atm} = 7.1 \times 10^6 \text{ Pa} ; \quad \rho = 1 \times 10^3 \text{ kg/m}^3$$

$$h = \frac{P - P_0}{\rho g} = \frac{7.1 \times 10^6}{1 \times 10^3 \times 9.8} = 720 \text{ m}$$

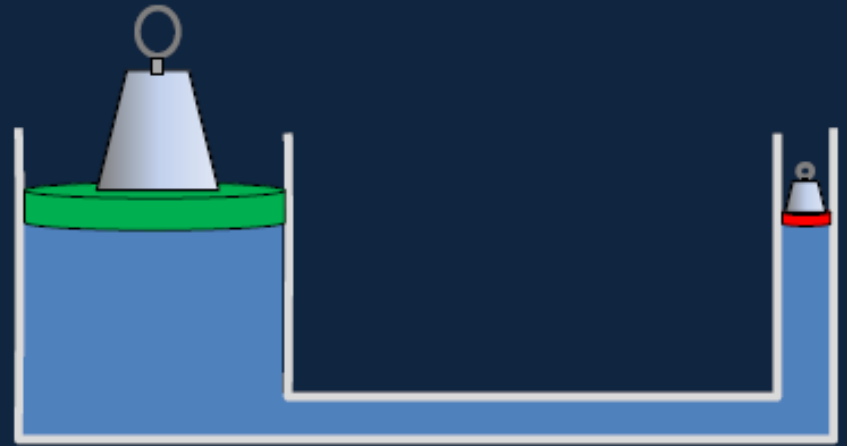
Pressure Same in all Directions

- At a point inside a fluid at rest, the pressure on a small area doesn't depend on which way the area is pointing.
- Imagine a small triangular wedge of the fluid, all at rest. The pressure forces on the sides must balance: they add to zero.
- The balance means the forces are proportional to the little areas, so the **pressure is the same**.



Pascal's Principle

- Added pressure to a fluid is transmitted through the fluid. This **increased pressure is still equal at equal depths.**
- The ratio of the balanced weights here is the ratio of the **green/red** areas.
- A small push on the small weight raises the big one—but not by much!

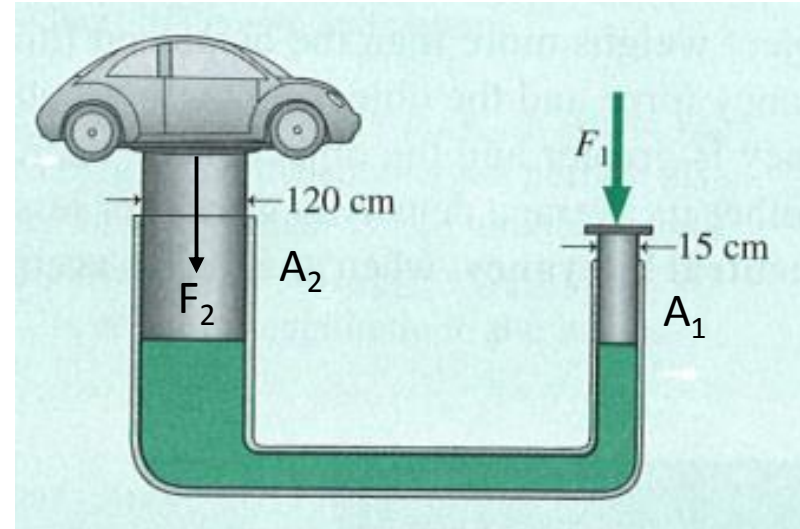


This is effectively a **lever**: the fluid is almost incompressible, so the distances traveled in small displacements are *inverse* to the areas, hence to the forces.

Pascal's Principle: Example

- Pressure force is transmitted through a fluid

Q. A large piston supports a car. The total mass of the piston and car is 3200 kg . What force must be applied to the smaller piston to support the car?



Pressure at the same height is the same!

$$\frac{F_1}{A_1} = \frac{F_2}{A_2} \quad F_1 = \frac{A_1}{A_2} mg = \frac{\pi \times 0.152}{\pi \times 1.202} \times 3200 \times 9.8 = 490\text{ N}$$

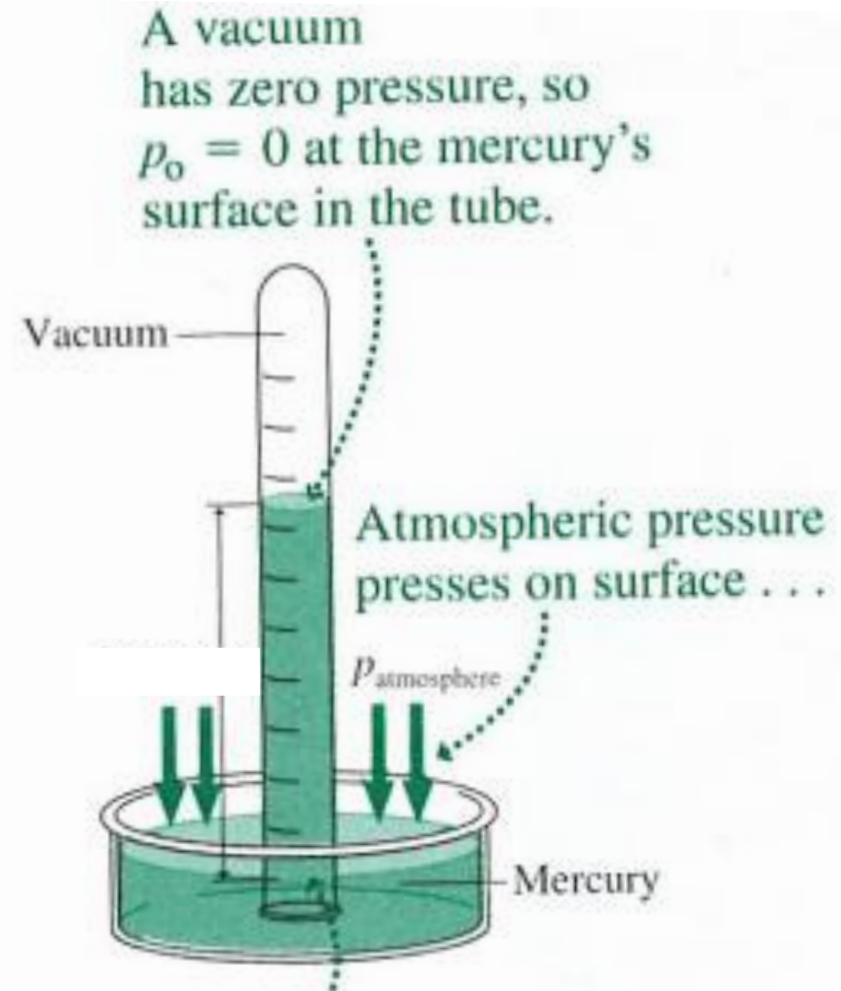
Measuring Pressure

Q. What is height of mercury (Hg) at 1 atm ?

$$\rho_{Hg} = 13.6 \text{ g/cm}^3$$

$$P = P_0 + \rho gh \rightarrow h = P/\rho g$$

$$h = \frac{1 \times 10^5}{1.36 \times 10^4 \times 9.8} = 0.75 \text{ m}$$

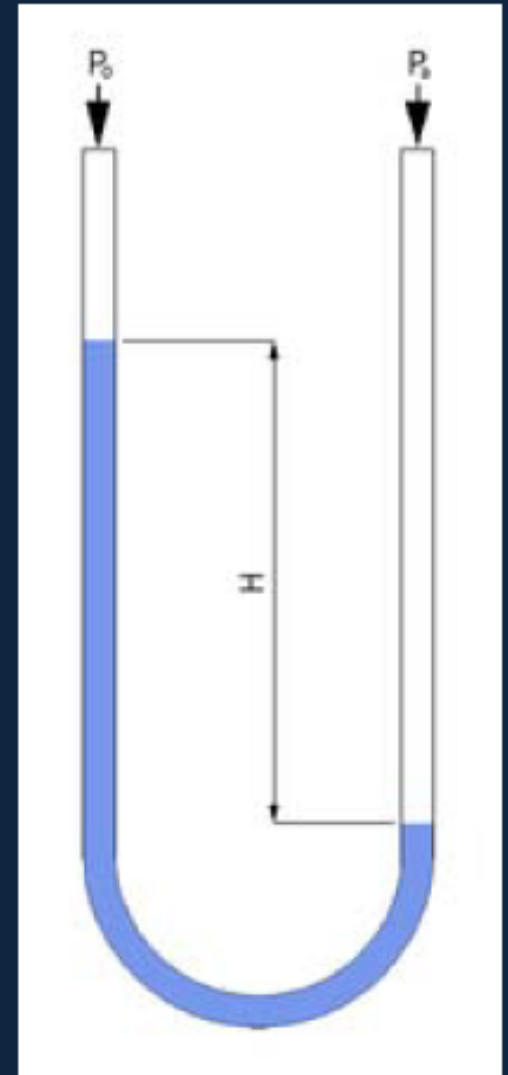


Atmospheric pressure can support a 10 meters high column of water. Moving to **higher density** fluids allows a table top **barometer** to be easily constructed.

$$p = p_0 + \rho gh$$

Absolute Pressure and Gauge Pressure

- A common pressure gauge is the manometer, a U-tube with liquid. The pressure difference between the two sides is ρgH .
- Tire pressures, for example, are measured **relative to atmospheric pressure**: this is called gauge pressure.
- Absolute pressure is relative to a vacuum. The absolute pressure in a swimming pool = $\rho gh + 1 \text{ atm}$.



Gauge Pressure



Gauge Pressure is the pressure difference from atmosphere. (e.g. Tyres)

$$P_{absolute} = P_{atmosphere} + P_{gauge}$$

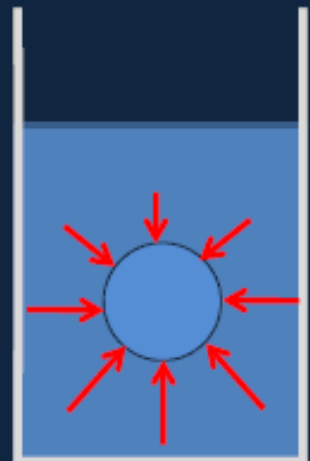
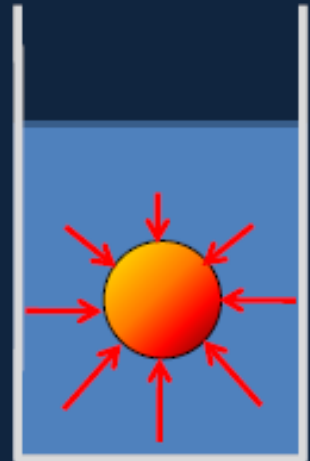
Archimedes' Principle and Buoyancy



Why do some things **float** and other things **sink** ?

Buoyancy Force

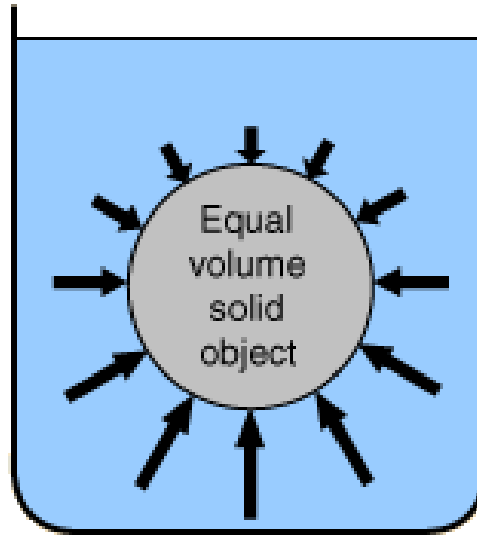
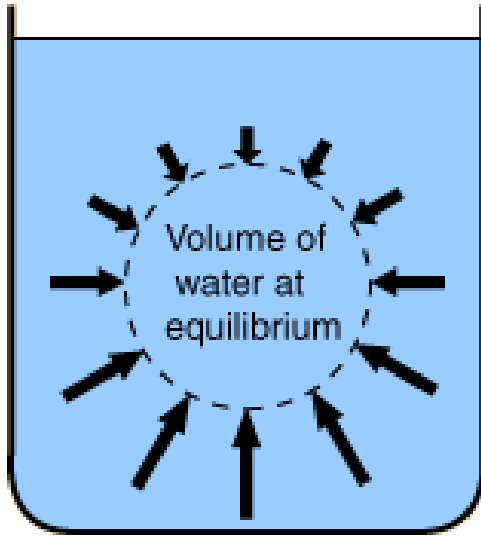
- Any object immersed in a fluid feels pressure forces all around it. Since the pressure is greater at greater depth, there is a **net upwards force**—this is called **buoyancy**.
- Suppose the underwater object is replaced with a ghost: an extremely thin plastic sheet of the same identical shape, just enclosing the fluid.
- **The pressure forces on this ghost will be identical, and they will be just enough to support the weight of the fluid inside.**



Archimedes' Principle and Buoyancy

Objects immersed in a fluid experience a Buoyant Force!

$$F_B = m_{water} g = \rho_{water} V g \quad (\text{up})$$



$F_B > W_{solid}$
Partly immersed

$F_B = W_{solid}$
Floating

$F_B < W_{solid}$
Sinks

$$W_{solid} = m_{solid} g = \rho_{solid} V g \quad (\text{down})$$

The **Buoyant Force** is equal to the weight of the **displaced fluid** !

Archimedes' Principle

- A body immersed (or partially immersed) in a fluid experiences a net upward buoyancy force equal to the weight of the fluid displaced.

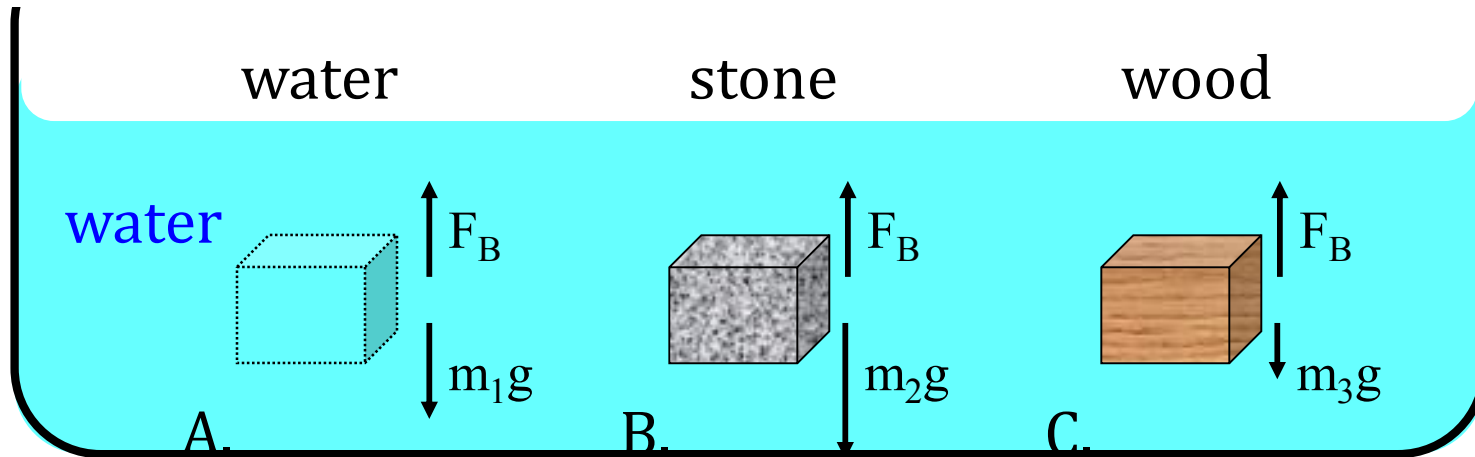
Archimedes' Principle and Buoyancy



The hot-air balloon floats because the **weight of air displaced** (= the buoyancy force) is greater than the **weight of the balloon**

The **Buoyant Force** is equal to the weight of the **displaced** fluid !

Which of the three cubes of length l shown below has the largest buoyant force?



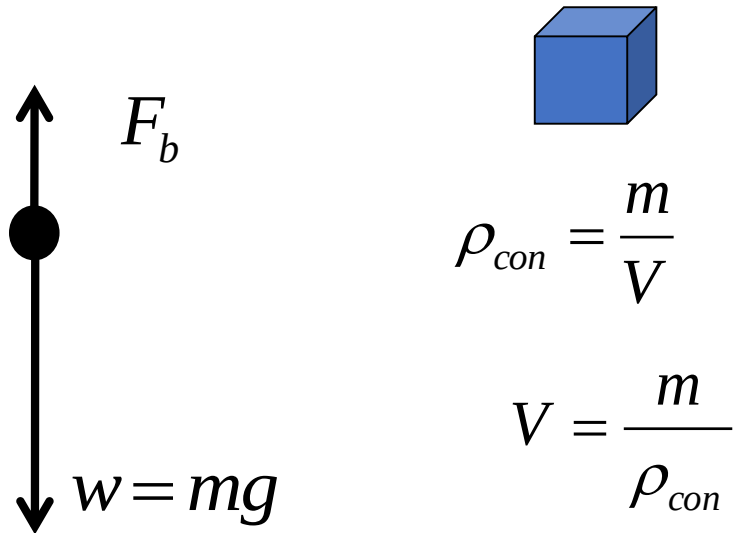
1. *water*
2. *stone*
3. *wood*
4. *the buoyant force is the same*
5. **Not enough information**

Example Archimedes' Principle and Buoyancy

Q. Find the apparent weight of a 60 kg concrete block when you lift it under water, $\rho_{\text{concrete}} = 2200\text{ kg/m}^3$

Solution

Water provides a buoyancy force
Apparent weight should be less



$$F_{\text{net}} = mg - F_b = w_{\text{apparent}}$$

$$F_b = m_{\text{disp water}} g = \rho_{\text{water}} V g$$

$$w_{\text{app}} = mg - \frac{\rho_{\text{water}} mg}{\rho_{\text{con}}}$$

$$w_{\text{app}} = mg \left(1 - \frac{\rho_{\text{water}}}{\rho_{\text{con}}}\right)$$

$$= 60 \times 9.8 \times \left(1 - \frac{1000}{2200}\right) = 321\text{ N}$$

Floating Objects

Q. If the density of an iceberg is 0.86 that of seawater, how much of an iceberg's volume is below the sea?

*Buoyancy force F_B
= weight of water displaced*

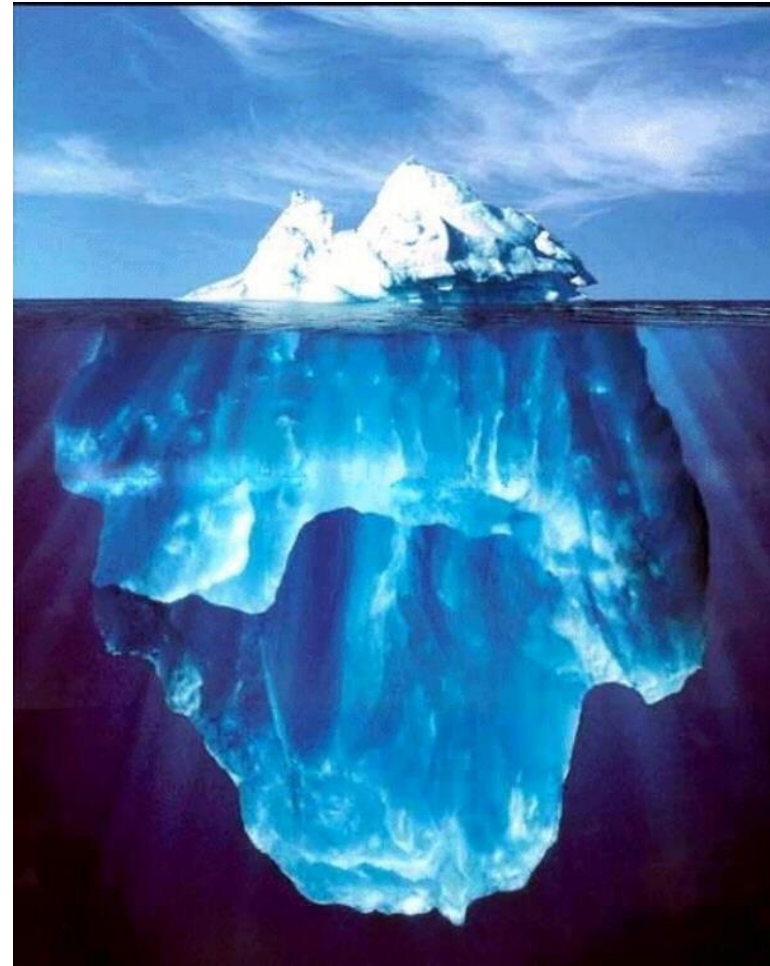
V_{sub} = submerged volume

$$F_B = m w_{ater} g = \rho_{water} V_{sub} g$$

*In equilibrium,
 F_B = weight of iceberg*

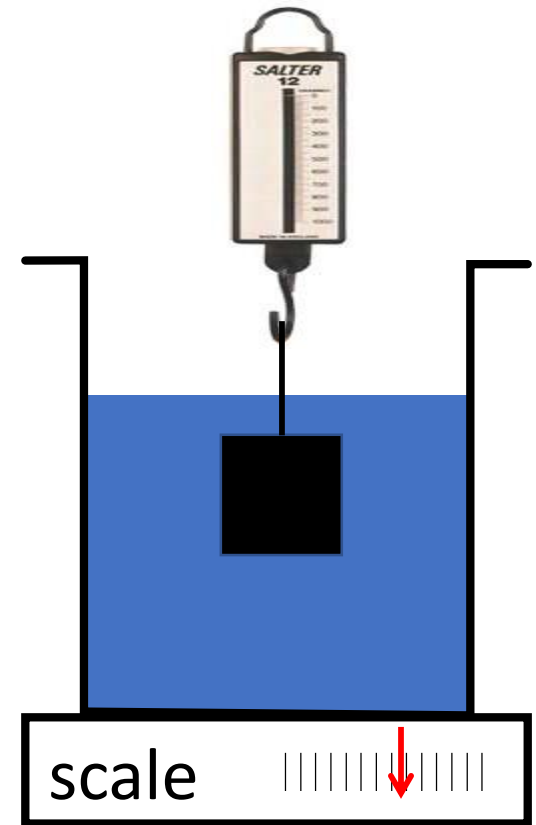
$$F_B = m i c_e g = \rho_{ice} V i c_e g$$

$$\rho_{water} V_{sub} g = \rho_{ice} V_{ice} g \rightarrow \frac{V_{sub}}{V_{ice}} = \frac{\rho_{water}}{\rho_{ice}} = 0.86$$

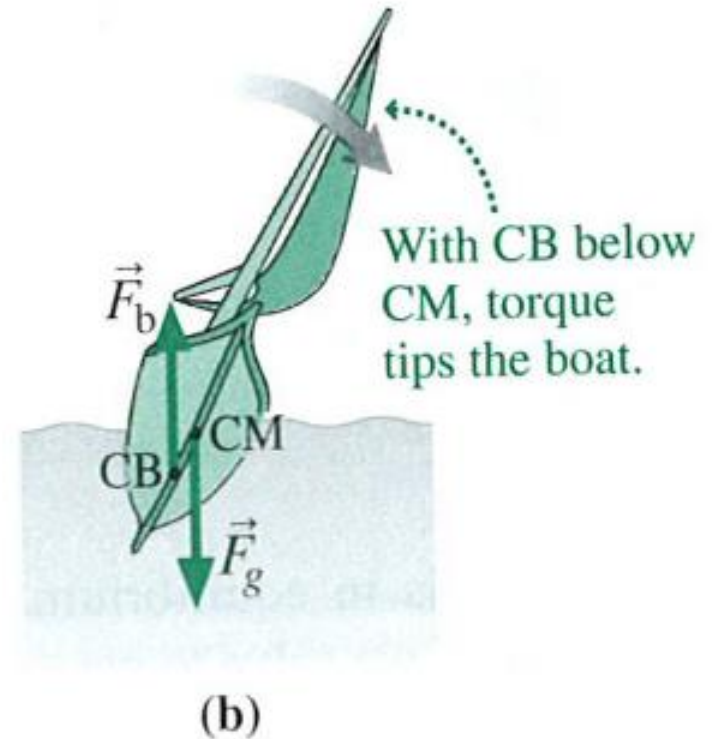
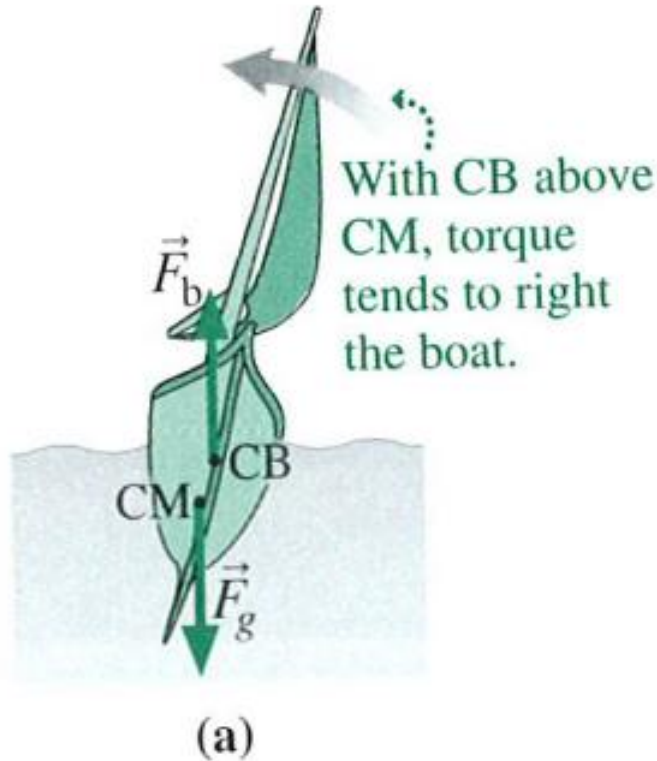


A beaker of water weighs w_1 . A block of weight w_2 is suspended in the water by a spring balance reading w_3 . What does the scale read?

1. w_1
2. $w_1 + w_2$
3. $w_1 + w_3$
4. $w_1 + w_2 - w_3$
5. $w_1 + w_3 - w_2$



Centre of Buoyancy: Example



The **Centre of Buoyancy** is given by the Centre of Mass of the **displaced** fluid. For objects to float with stability the Centre of Buoyancy must be **above** the Centre of Mass of the object. Otherwise Torque yield Tip !

Fluid Dynamics

Laminar (steady) flow is where each particle in the fluid moves along a smooth path, and the paths do not cross.

The path is called a **streamline**.

Velocity is **tangent** to the streamline for steady flow don't cross.

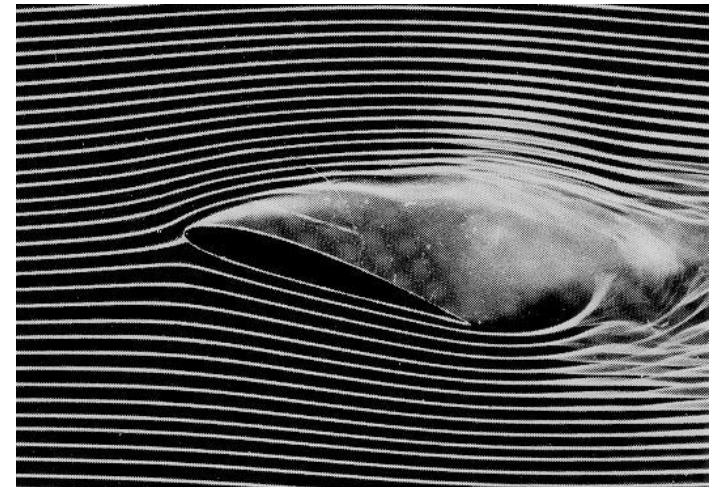
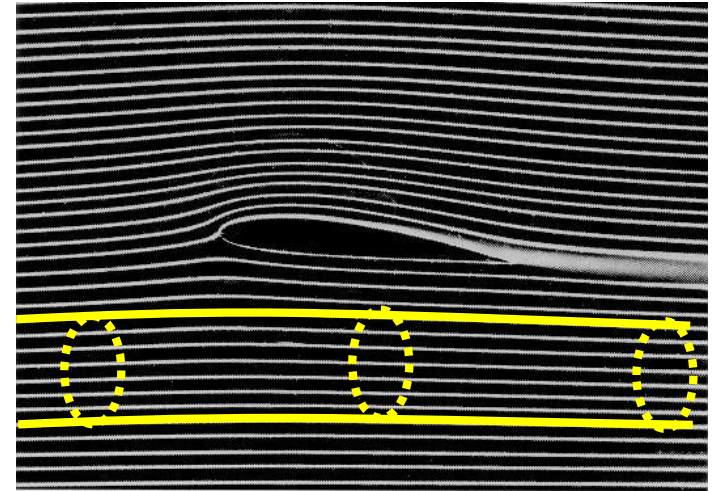
Spacing of streamlines measures **speed**.

A set of streamlines act as a pipe for an **incompressible** fluid.

Non-viscous flow – no internal friction (water OK, honey not)

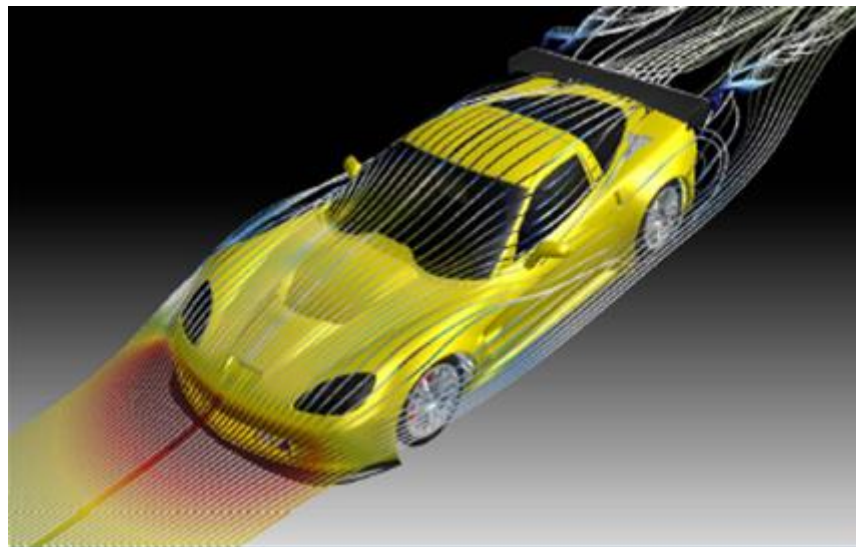
Turbulent flow above a **critical speed**.

Whirlpools appear, paths cross, and become irregular and chaotic.

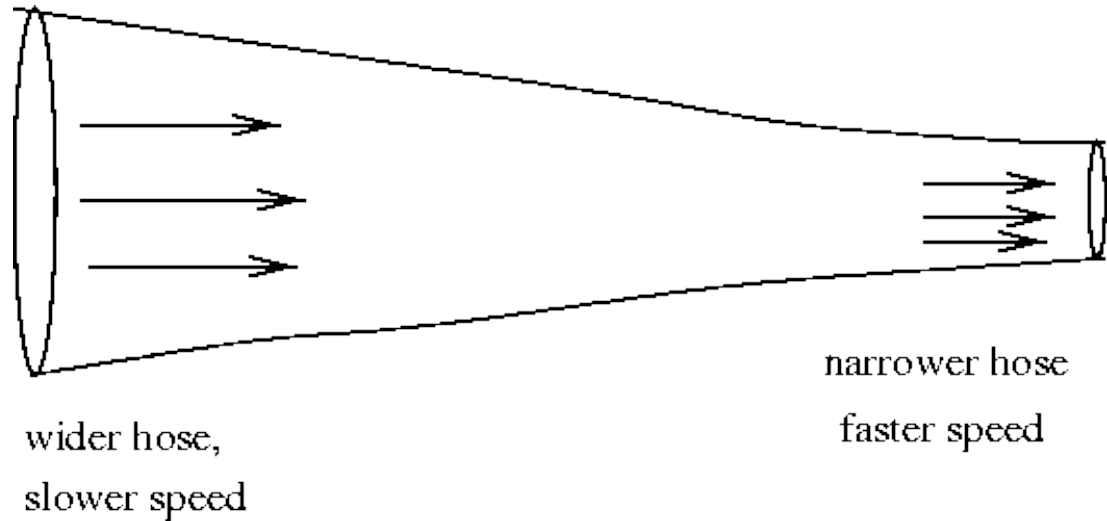


LAMINAR AT THE FRONT AND TURBULENT AT THE BACK

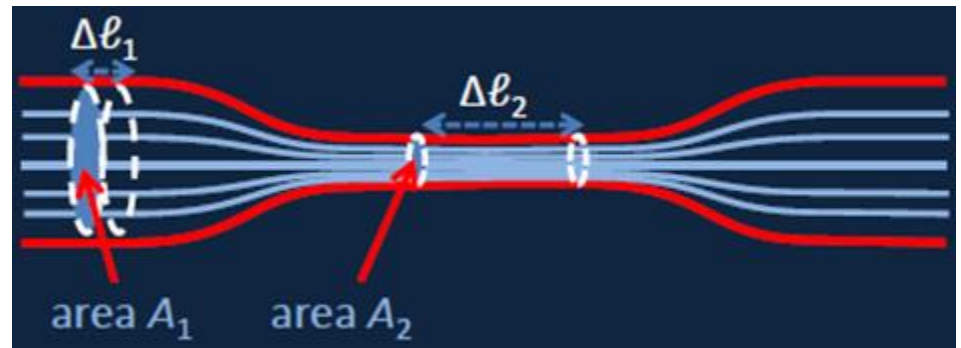
Air flow over this Corvette is **laminar** until the end: the air cannot curve in completely at the back, it breaks away forming a **turbulent** wake.



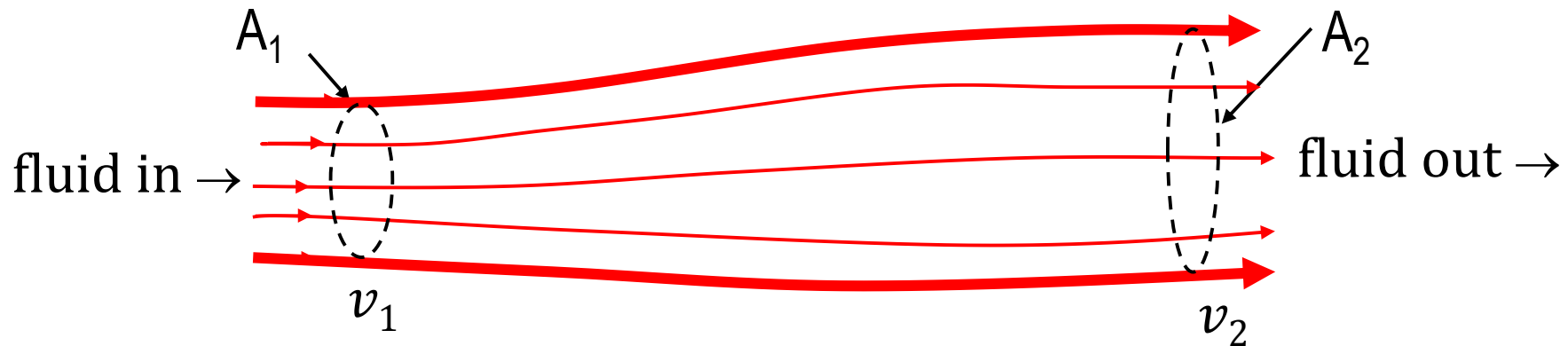
Conservation of Mass: The Continuity Eqn.



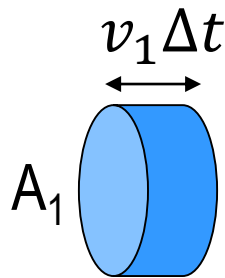
The rate of flow is the **same** at all cross-sections.
There can be **no sources or sinks** of fluid.



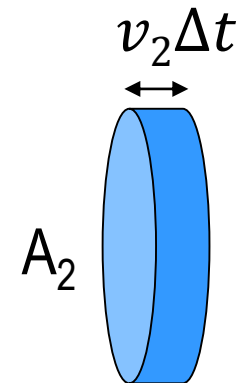
Conservation of Mass: The Continuity Eqn.



Q. How much fluid flows across each area in a time Δt :



$$\Delta m = \rho_1 V_1 = \rho_1 A_1 v_1 \Delta t$$



$$\Delta m = \rho_2 V_2 = \rho_2 A_2 v_2 \Delta t$$

$$\text{flow rate: } \frac{\Delta m}{\Delta t} = \rho A v$$

$$\text{Continuity eqn: } \rho_1 A_1 v_1 = \rho_2 A_2 v_2$$

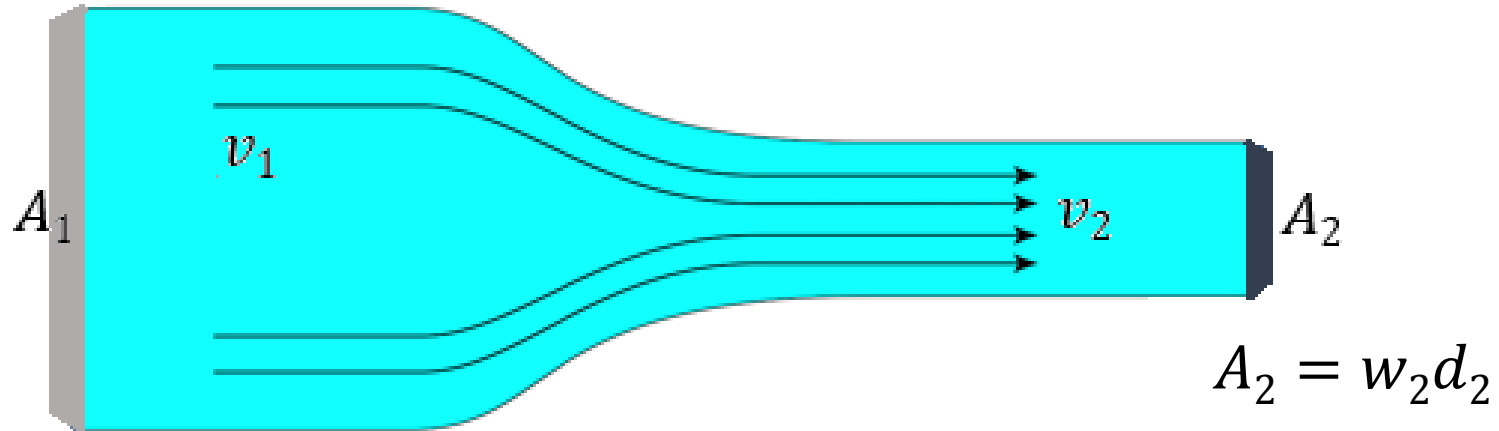
Continuity equation for incompressible fluid

- Density is constant for incompressible fluid.
- The continuity equation then becomes

$$A_1 v_1 = A_2 v_2$$

Conservation of Mass: The Continuity Eqn.

Q. A river is 40m wide, 2.2m deep and flows at 4.5 m/s. It passes through a 3.7-m wide gorge, where the flow rate increases to 6.0 m/s. How deep is the gorge?

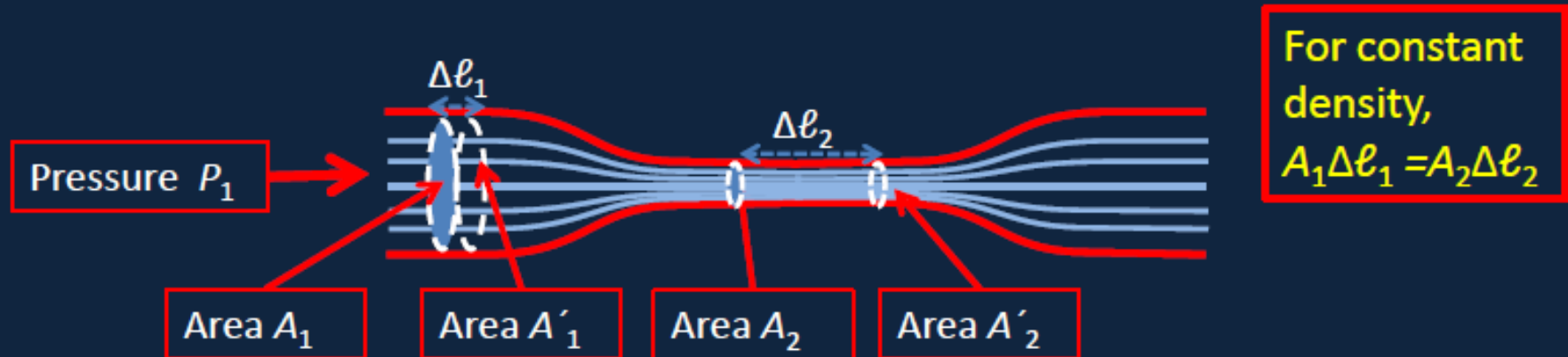


$$A_1 = w_1 d_1$$

Continuity equation : $A_1 v_1 = A_2 v_2 \rightarrow w_1 d_1 v_1 = w_2 d_2 v_2$

$$d_2 = \frac{w_1 d_1 v_1}{w_2 v_2} = \frac{40 \times 2.2 \times 4.5}{3.7 \times 6.0} = 18 \text{ m}$$

Bernoulli's Equation

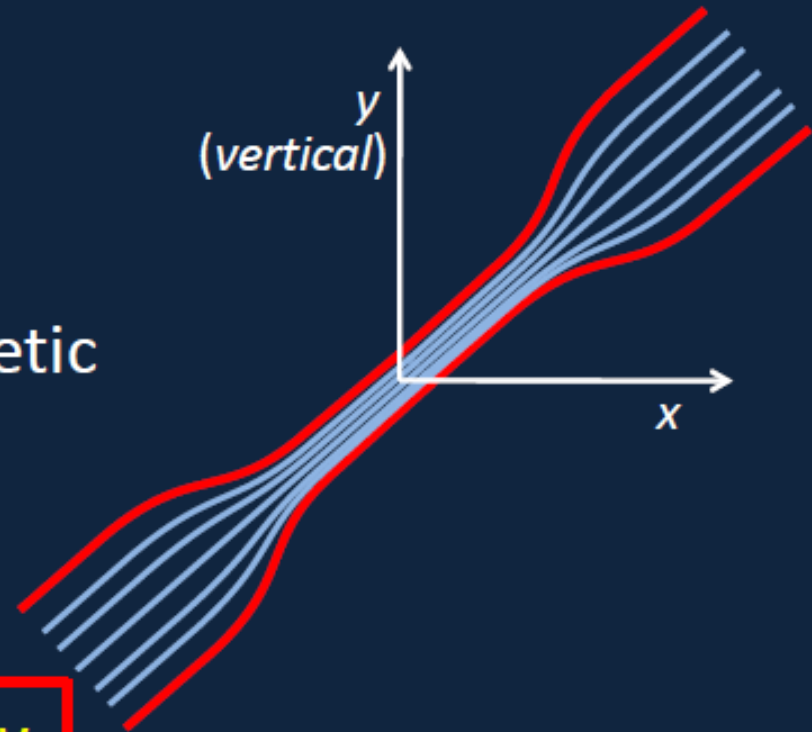


- In the time Δt , there is a **KE gain** of $\frac{1}{2}\rho A_1 \Delta \ell_1 (v_2^2 - v_1^2)$.
- Where did that energy come from?
- In the time Δt , the **pressure P_1 on the area A_1 does work**:
force x distance = $P_1 A_1 \Delta \ell_1$
- **BUT** at the same time, our block of fluid did some work itself:
it pushed the fluid in front of it, doing work = $P_2 A_2 \Delta \ell_2$.
- **SO** net work done = $(P_1 - P_2) A_1 \Delta \ell_1 = \text{KE gain } \frac{1}{2}\rho A_1 \Delta \ell_1 (v_2^2 - v_1^2)$
- That is, $P_1 + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2$

Uphill Work...

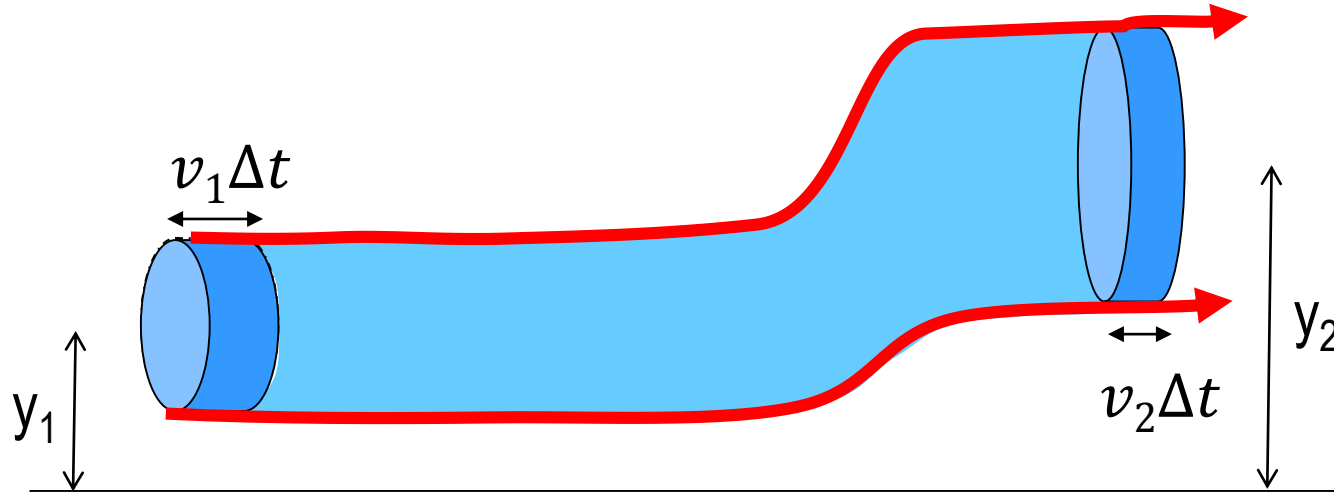
- What if the pipe is *tilted upwards*?
- Now the pressure speeding the fluid along has to lift it as well!
- So the pressure adds potential energy corresponding to how much it was lifted as well as kinetic energy from speeding it up.
- This gives the full Bernoulli's equation:

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g y_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g y_2$$



Conservation of Energy: Bernoulli's Eqn.

What happens to the energy density of the fluid if I raise the ends ?



Energy per unit
volume

$$p_1 + \frac{1}{2} \rho v_1^2 + \rho g y_1 = p_2 + \frac{1}{2} \rho v_2^2 + \rho g y_2 = \text{const}$$

Total energy per unit volume is constant
at **any** point in fluid.

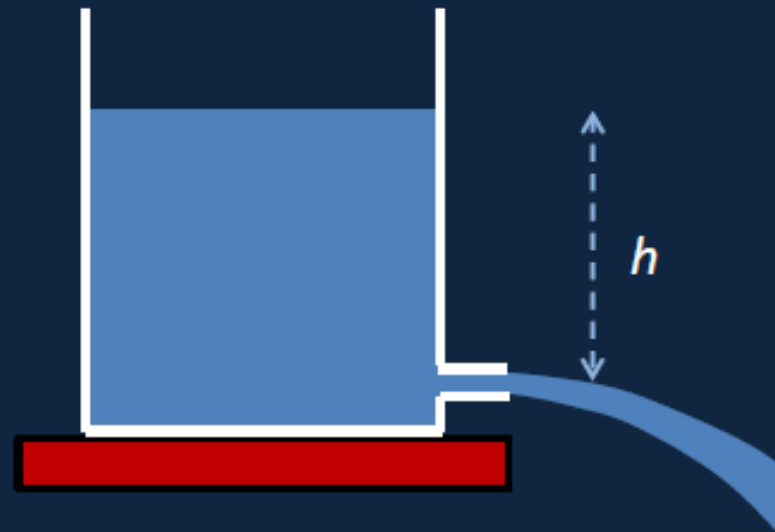
$$p + \frac{1}{2} \rho v^2 + \rho g y = \text{const}$$

Torricelli's Theorem

- Water coming from a small spigot in a large tank has a speed given by

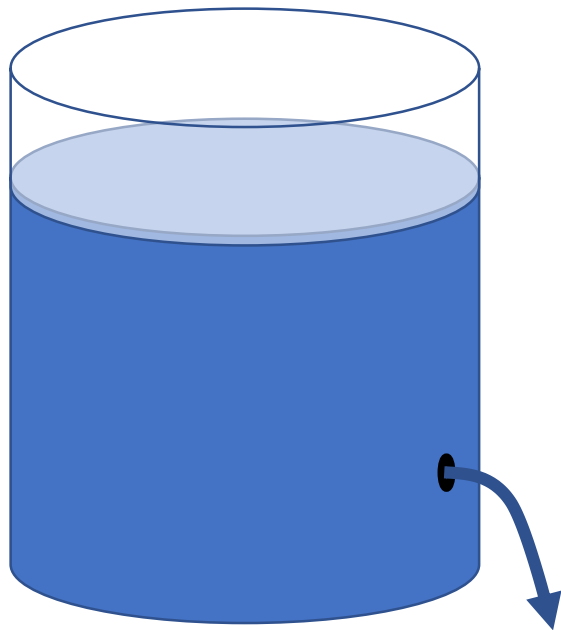
$$v^2 = 2gh$$

- This is a special case of Bernoulli's equation, because the outside pressure at the spigot is the same as that at the top of the fluid, and fluid velocity at the top is negligible.



Conservation of Energy: Bernoulli's Eqn.

Q. Find the velocity of water leaving a tank through a hole in the side 1 metre below the water level.



$$P + \frac{1}{2}\rho v^2 + \rho g y = \text{constant}$$

$$\text{At the top: } P = 1 \text{ atm}, v = 0, y = 1 \text{ m}$$

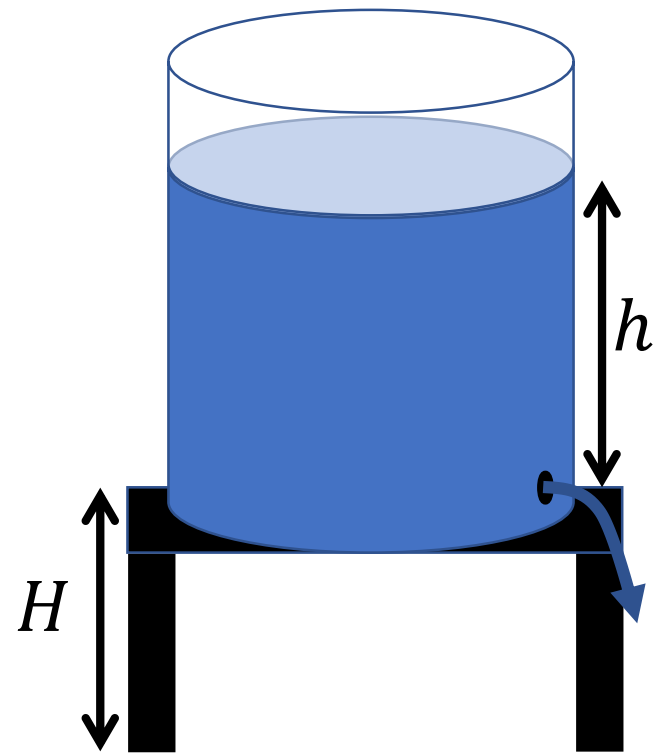
$$\text{At the bottom: } P = 1 \text{ atm}, v = ?, y = 0 \text{ m}$$

$$P + \rho g y = P + \frac{1}{2}\rho v^2$$

$$v = \sqrt{2gy} = \sqrt{2 \times 9.8 \times 1} = 4.4 \text{ m/s}$$

Which of the following can be done to increase the **flow rate** out of the water tank ?

1. Raise the tank ($\uparrow H$)
2. Reduce the hole size
3. Lower the water level ($\downarrow h$)
4. Raise the water level ($\uparrow h$)
5. None of the above



Summary: fluid dynamics



Continuity equation: mass is conserved!

$$\rho v A = \text{constant}$$

For liquids:

$$\rho = \text{constant} \rightarrow v A = \text{constant}$$

(Density ρ , velocity v , pipe area A)

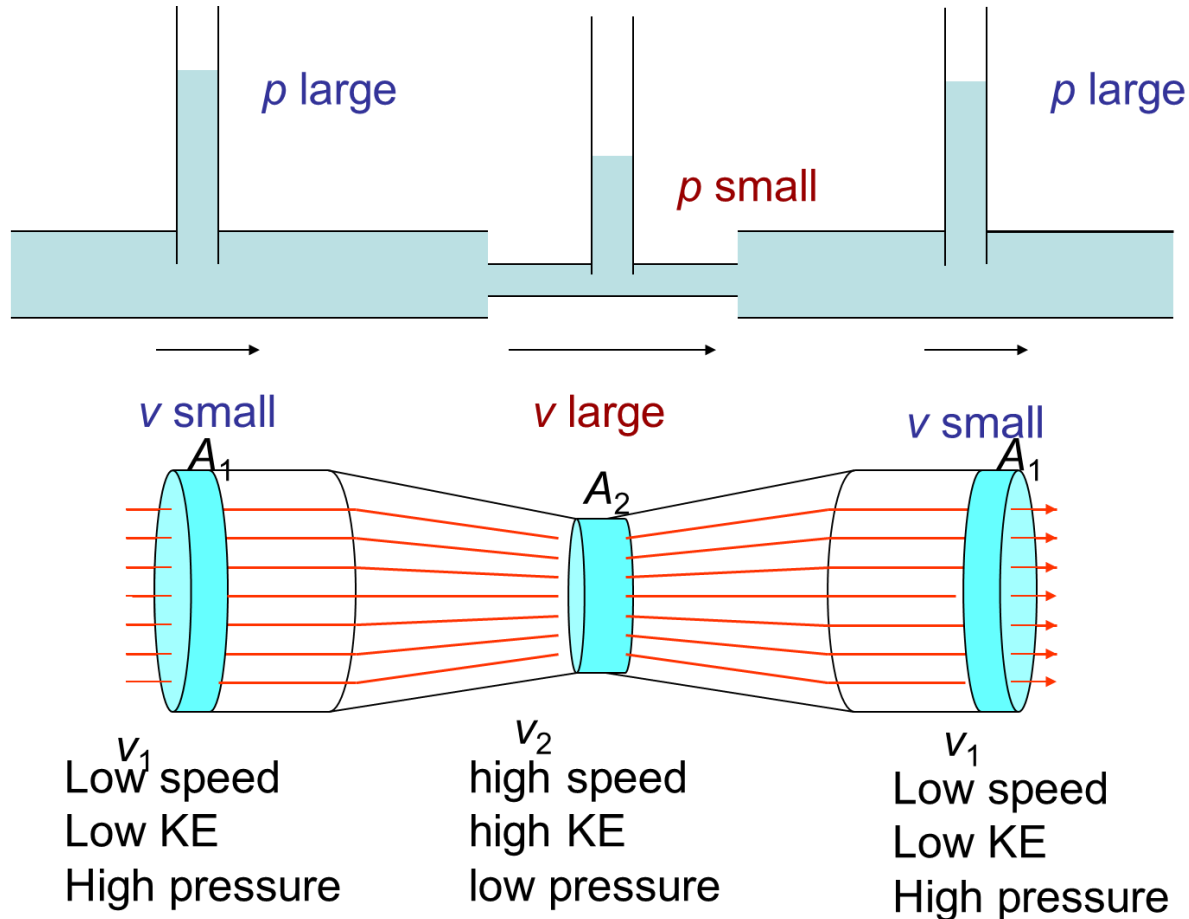
Bernoulli's equation: energy is conserved!

$$P + \frac{1}{2}\rho v^2 + \rho g y = \text{constant}$$

(Pressure P , density ρ , velocity v , height y)

Applications of Bernoulli's Principle

- Venturi and pitot tubes



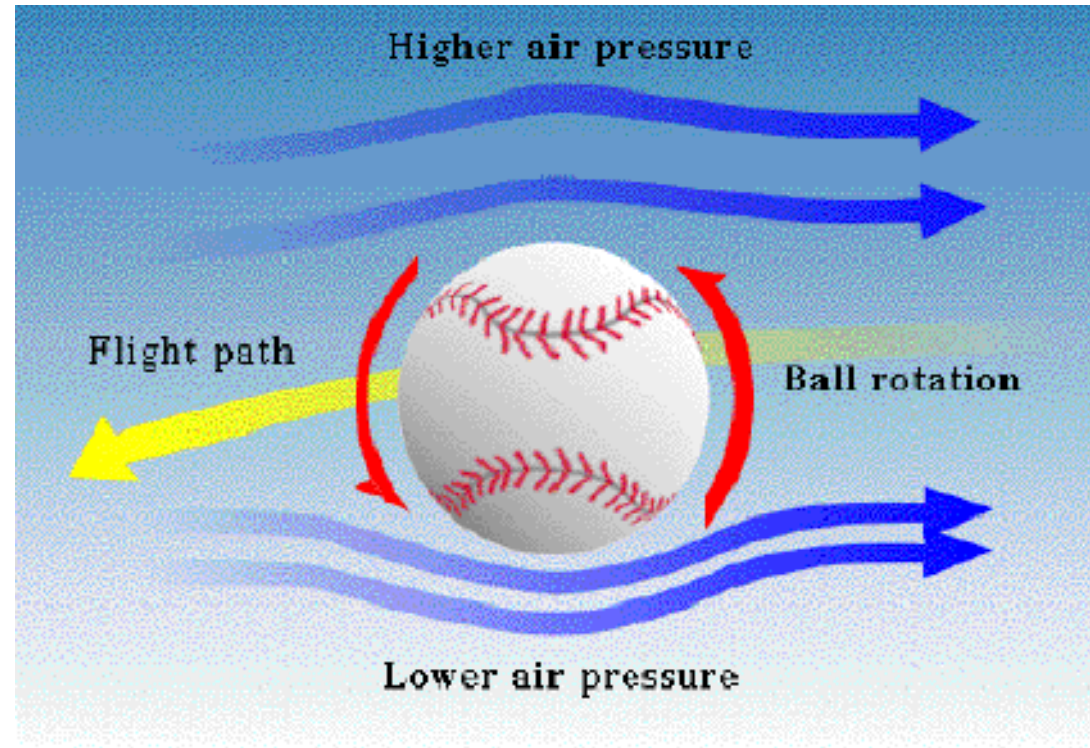
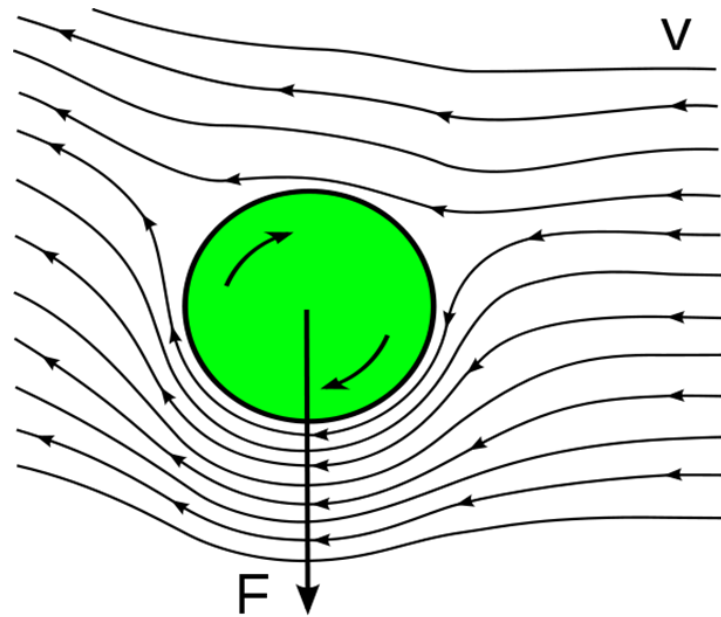
Applications of Bernoulli's Principle

- Scent pray

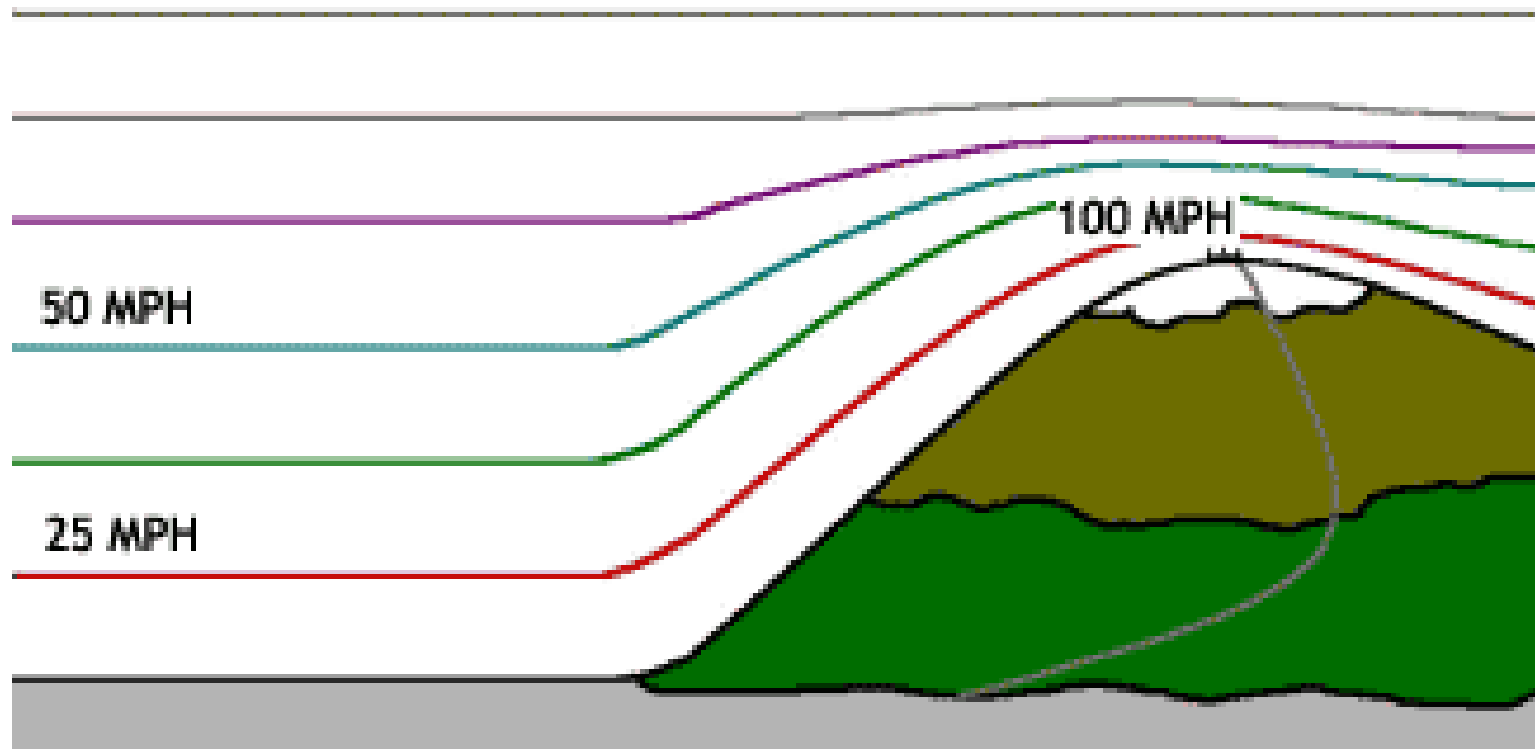


Applications of Bernoulli's Principle

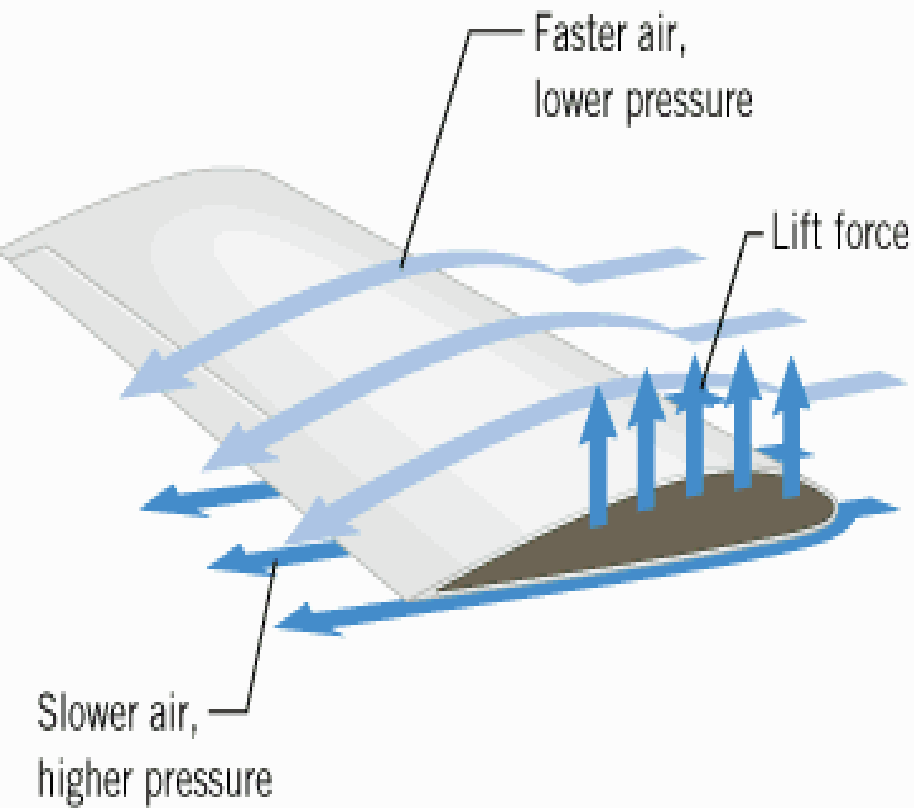
- Swerving ball



Applications of Bernoulli's Principle



Applications of Bernoulli's Principle



(a)



(b)

Applications of Bernoulli's Principle



Properties of Bulk Matter

Reading assignment

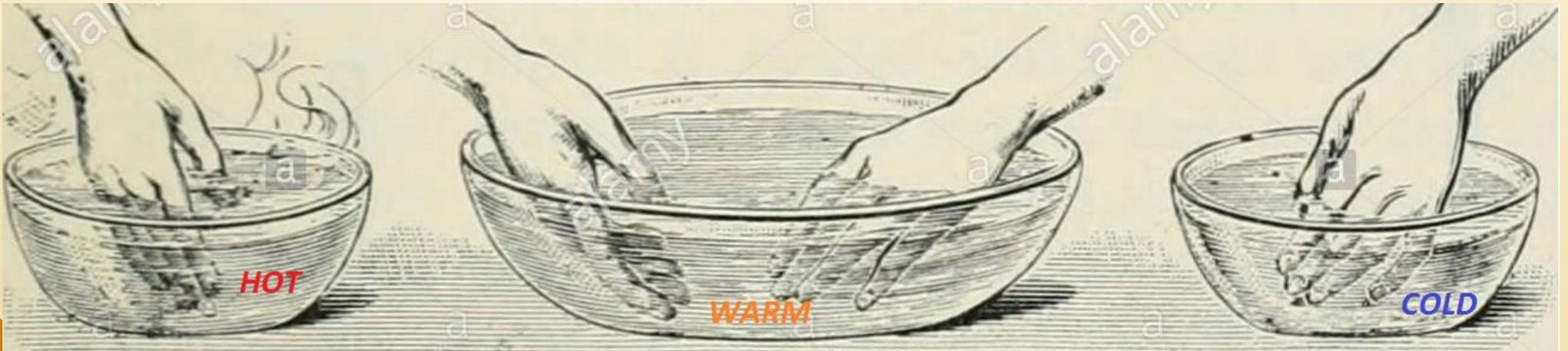
The top-left corner of the slide features a decorative graphic consisting of several overlapping, parallel lines. These lines are colored in a dark grey-blue and a mustard yellow, creating a layered, geometric effect that extends diagonally across the upper left portion of the frame.

Chapter 4

Heat and Thermodynamics

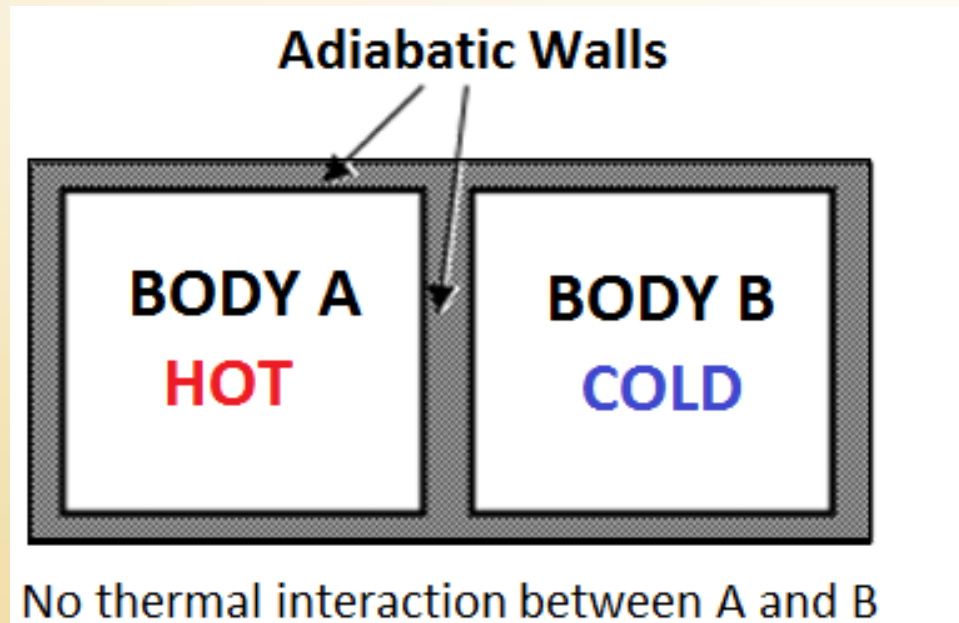
The Concept of Temperature and Heat

- What is temperature?
 - Qualitatively, based on our senses, **TEMPERATURE** is a physical quantity that tells us how warm or cold an object is.
 - This qualitative definition does not answer the question “how hot is hot?”
 - Also, our senses are misleading



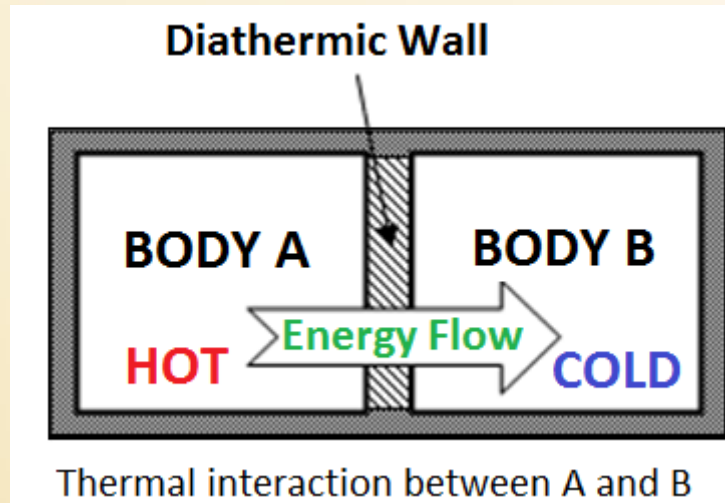
The Concept of Temperature and Heat

- What is temperature?
 - We need an *operational definition* of temperature.
 - Consider two bodies A and B, A being hotter than B, thermally isolated from each other.



- What happens when thermal contact is established between A and B?

The Concept of Temperature and Heat



- **Heat** is **energy in transfer** from a hot to a cold body.
- Objects are in **thermal contact** if heat can flow between them.
- Eventually, the energy flow stops.
- The two bodies will be in ***thermal equilibrium***.
- They are said to be at the same ***temperature***.

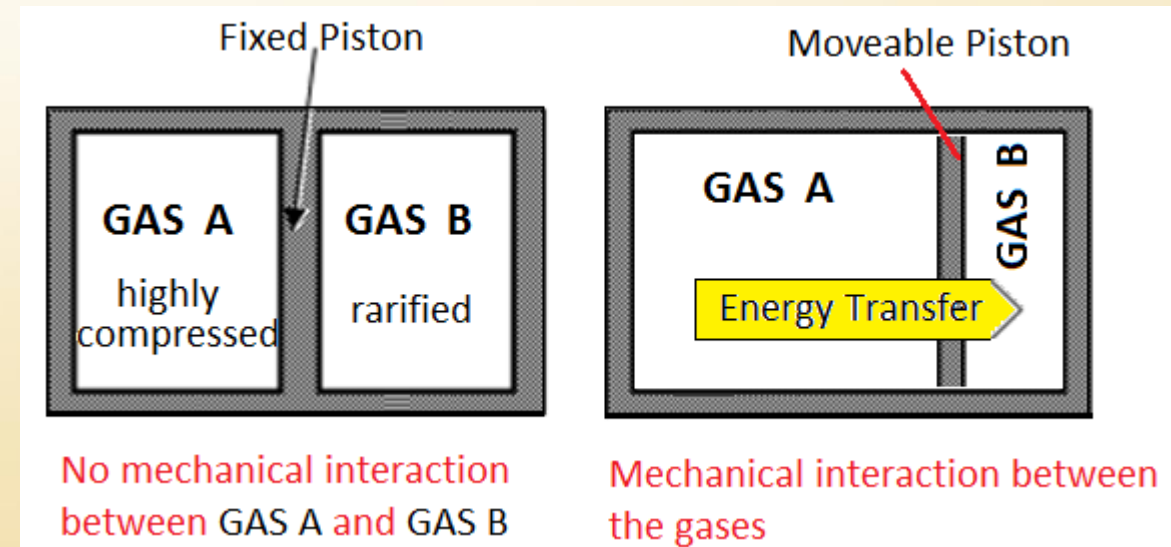
The Concept of Temperature and Heat

- Definition of temperature

*There is a scalar quantity called **temperature** that assumes the same value for bodies in thermal equilibrium.*

- Mechanical Analogy

*There is a quantity called **pressure** that assumes the same value for bodies in mechanical equilibrium.*

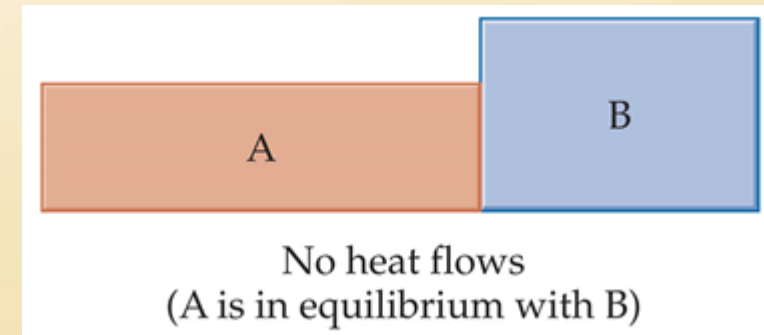
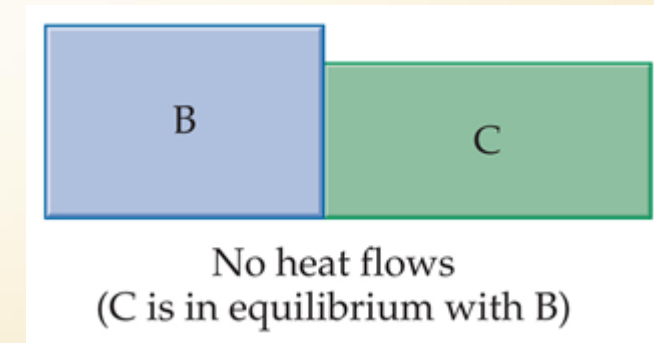
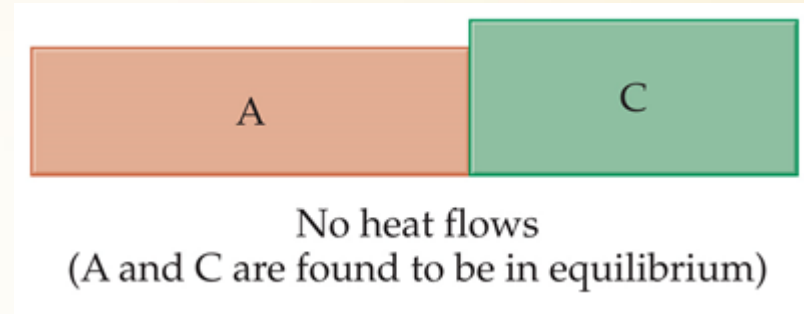


The Zeroth Law of Thermodynamics

Let's now introduce a third body C

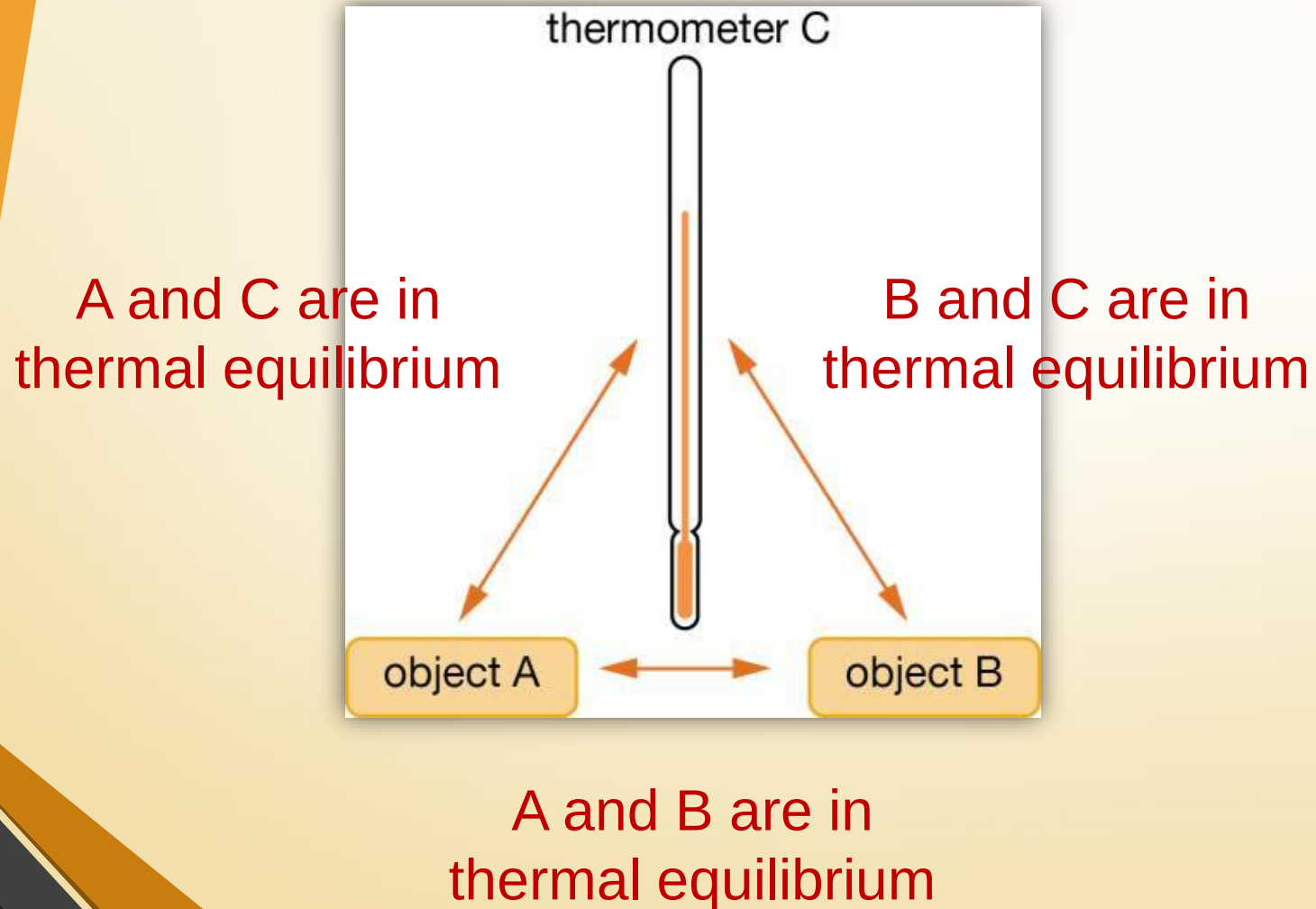
ZEROTH LAW OF THERMODYNAMICS

If bodies A and B are **separately** in thermal equilibrium with a third body C, then bodies A and B will be in thermal equilibrium if they are placed in thermal contact.



The Zeroth Law of Thermodynamics

What is the third body C? **The third body is a thermometer.**



A thermometer is an instrument that measures the temperature of a body in a quantitative way.

Temperature is the only factor that determines whether two objects in thermal contact are in thermal equilibrium or not.

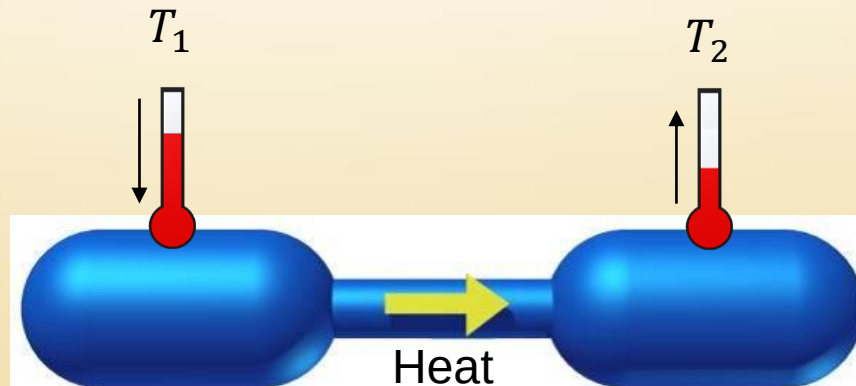
Thermal Energy (Heat) *versus* Temperature

Thermal Energy (Heat)

- is kinetic energy in transit from one object to another due to **temperature difference**.
- Measured in calories or Joules
- Any object with temperature above zero Kelvin has thermal energy

Temperature

- is the average kinetic energy of particles in an object – not the total amount of kinetic energy particles.
- Measured in °C, °F, K
- Absolute zero is zero Kelvin

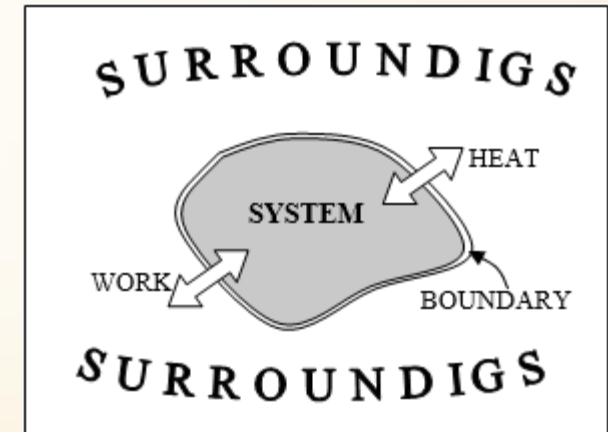


Quiz

- **The zeroth law of thermodynamics is**
 - A. A logical necessity**
 - B. An empirical fact** ●
 - C. A universal law**
 - D. Transitivity of thermal equilibrium** ●

Thermodynamics

- The study of the effects of work, heat, and energy on a **system**
- A **thermodynamic system** is a definite quantity of matter enclosed by boundaries, either real or imaginary.
- Everything outside the boundary is called the **surroundings**.
- The system may interact with the surroundings by interchanging energy through a transfer of *heat* and/or the performance of mechanical *work*.



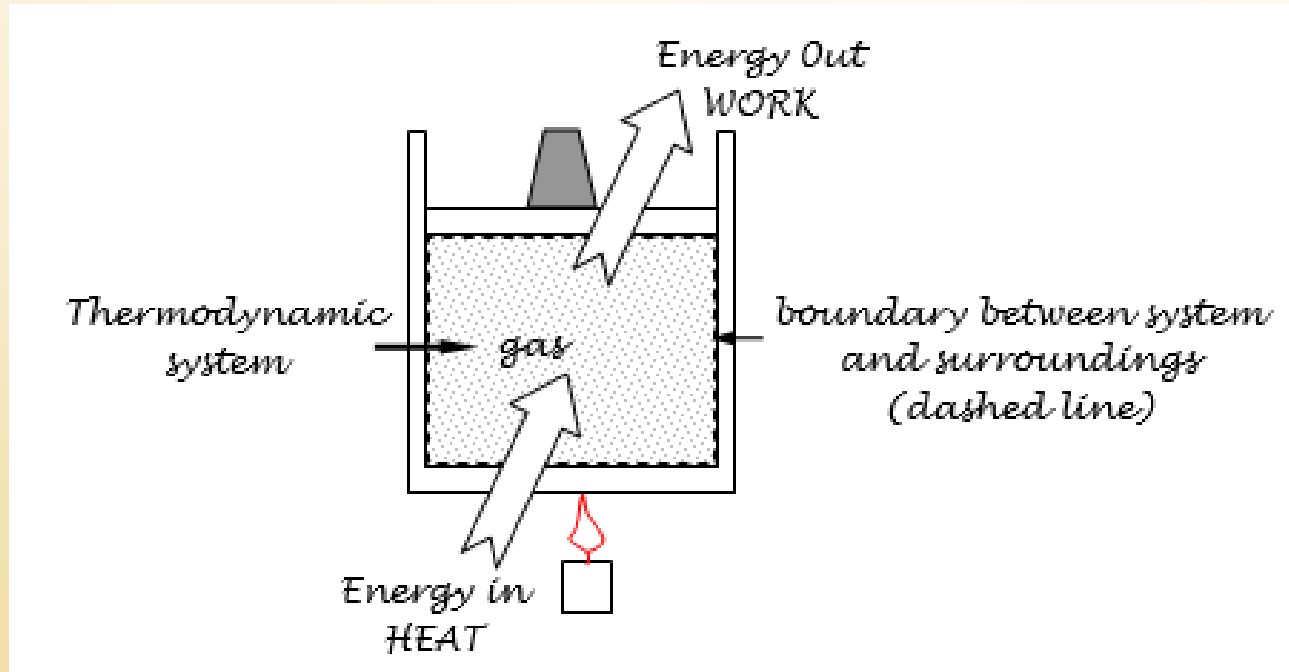
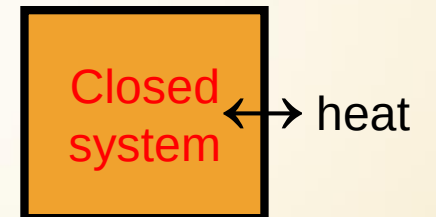
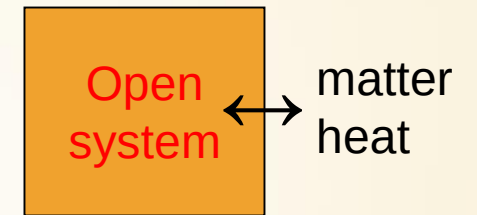
Thermal energy flows from hot to cold

- Identify the system and the surroundings
- Indicate the direction of energy flow



Thermodynamic Systems

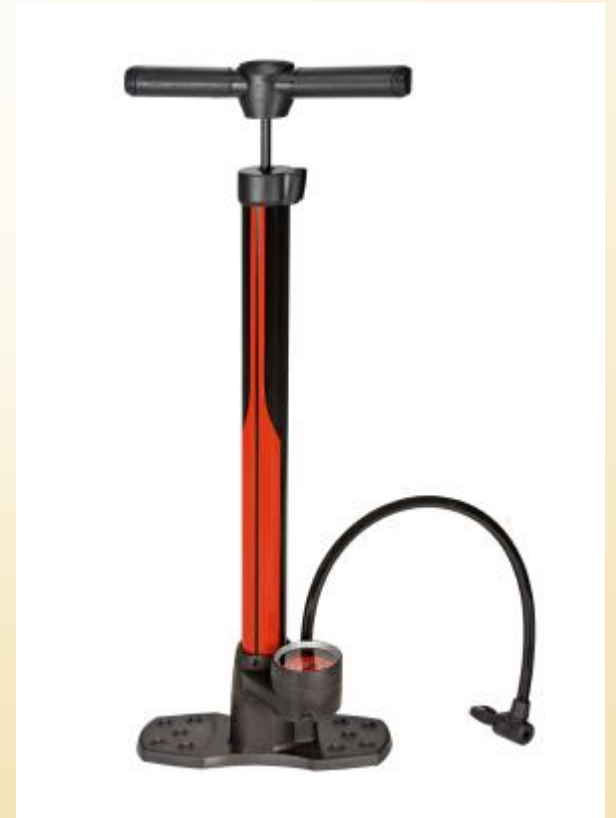
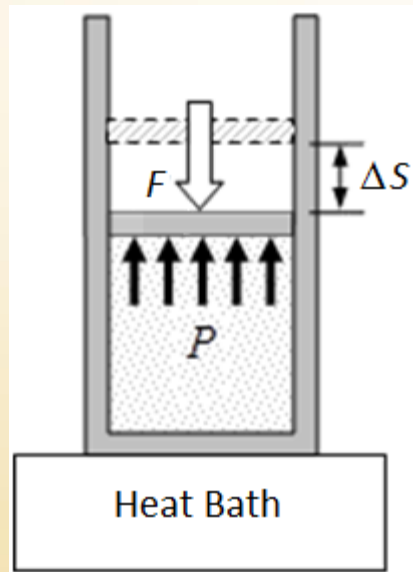
- Open → when matter CAN cross the boundary
- Closed → when matter CANNOT cross the boundary
- Isolated → Boundary seals matter and heat from being exchanged



Work – Mechanical Energy Transfer

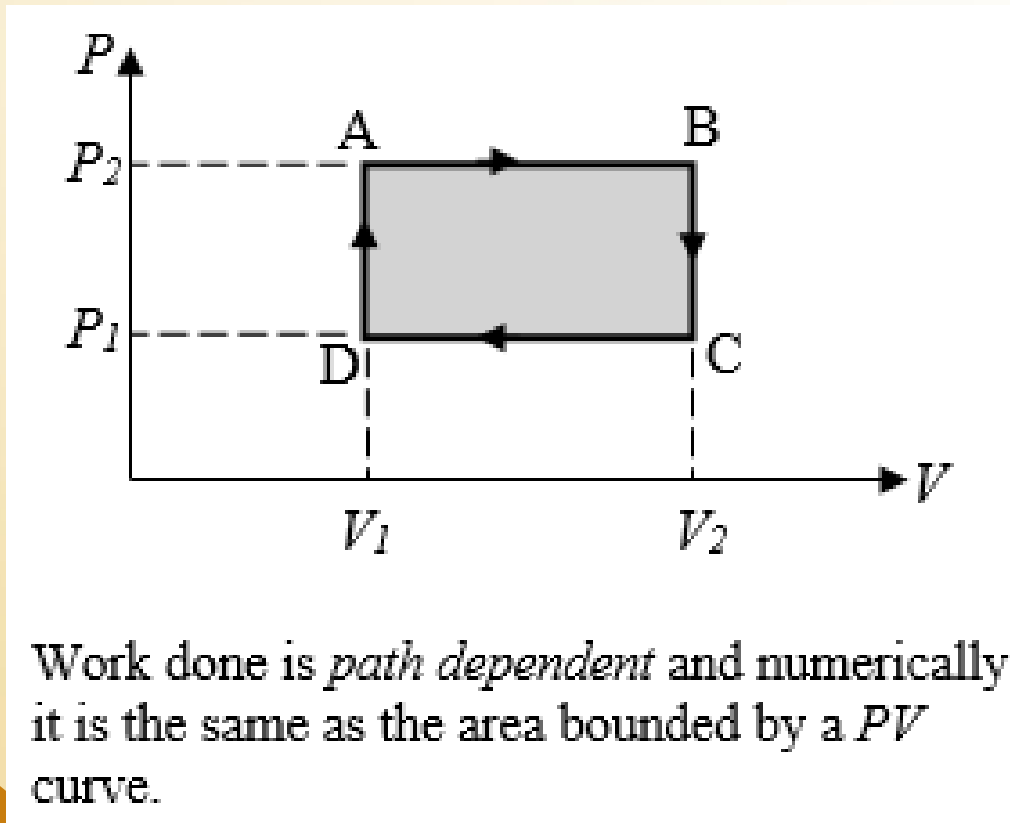
- Work done by expanding gas

$$W = -F\Delta s = -P\Delta V$$



Work – Mechanical Energy Transfer

- Work done depends on the thermodynamic process.



- Similarly, heat absorbed or rejected by a system depends on the thermodynamic process.

Internal Energy

Translation



Rotation



Vibration



Molecular Interactions



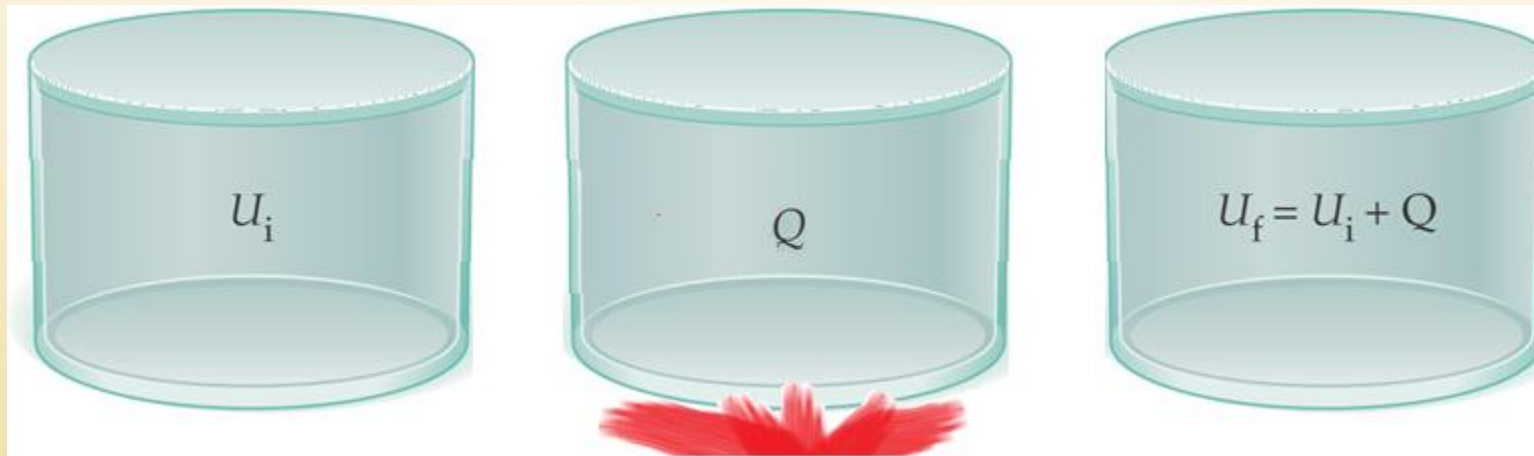
The internal energy of a system is the sum of the **kinetic** and **potential** energies of the atoms and molecules making up the system.

The First Law of Thermodynamics

The first law of thermodynamics is a statement of the conservation of energy.

If a system's volume is **constant**, and heat is added, its internal energy increases.

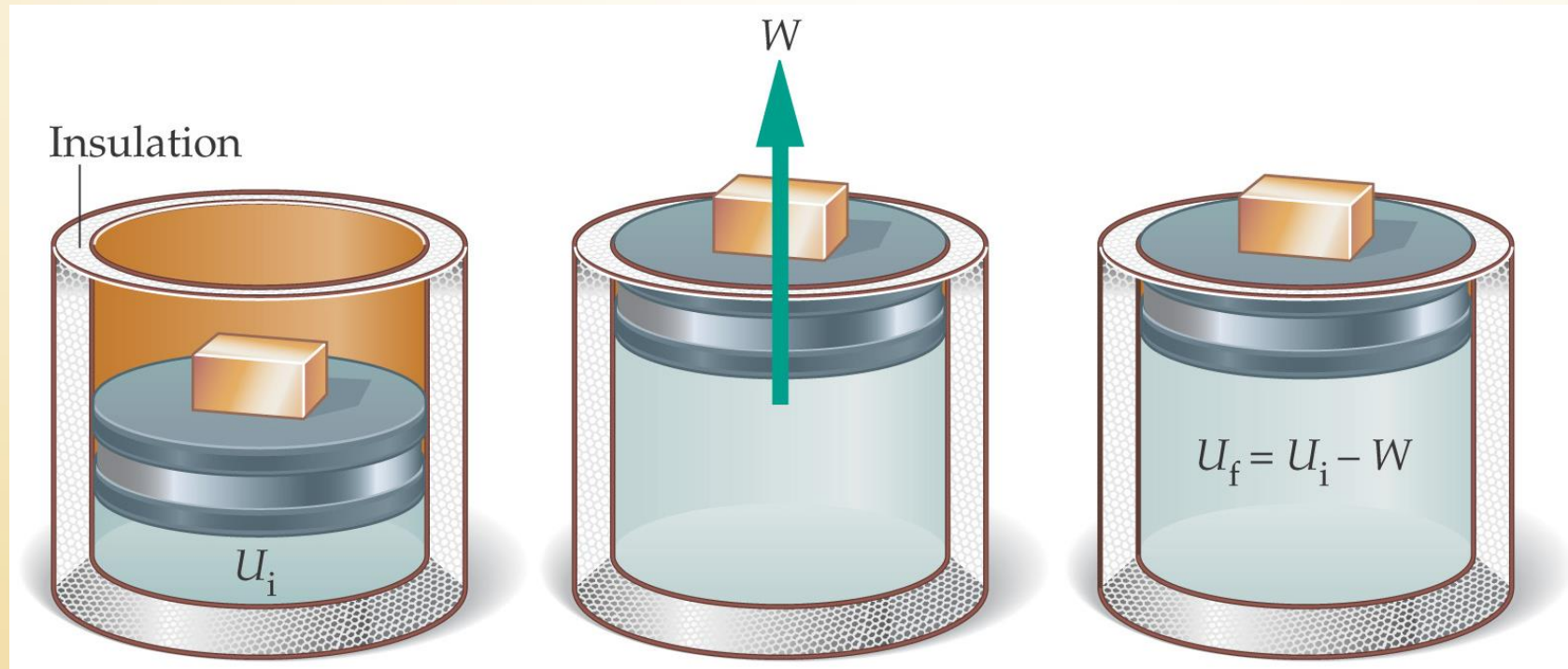
$$\Delta U = U_f - U_i = Q$$



The First Law of Thermodynamics

If a system does work on the external world, and no heat is added, its internal energy decreases.

$$\Delta U = U_f - U_i = -W$$



The First Law of Thermodynamics

Combining these gives the first law of thermodynamics.

$$\Delta U = Q - W$$

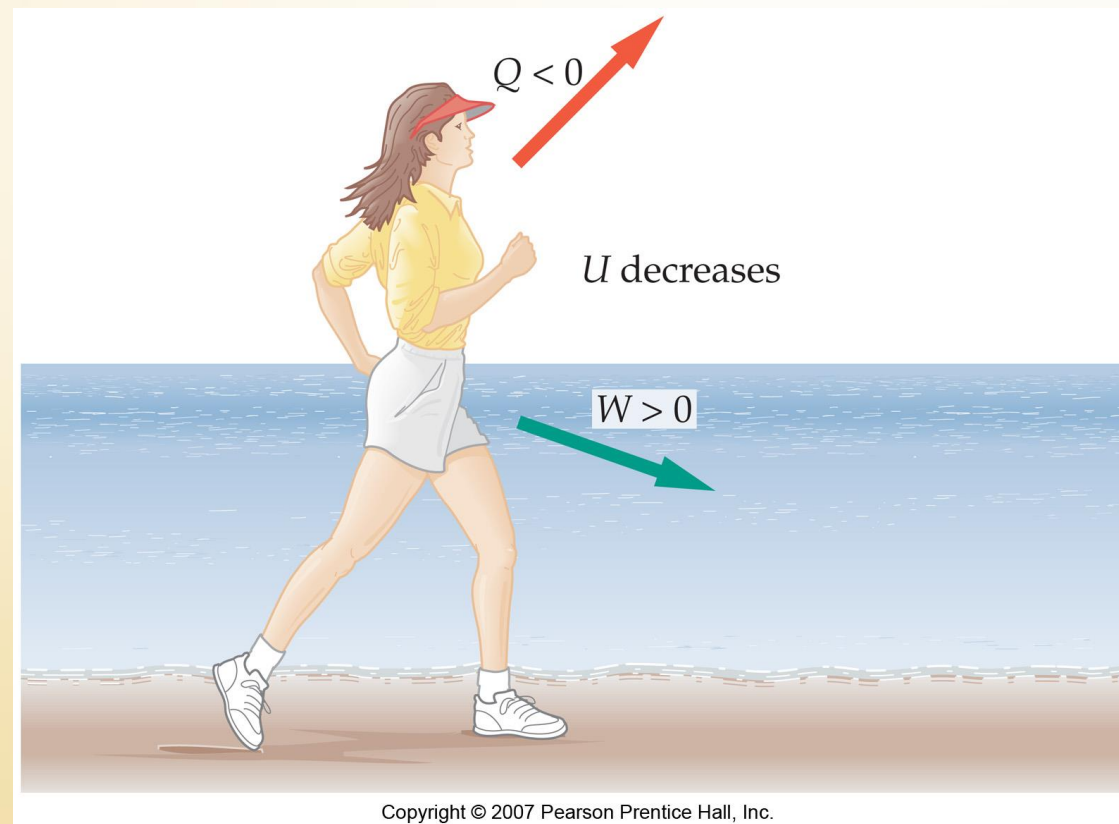
It is vital to keep track of the signs of Q and W .

TABLE 18–1 Signs of Q and W

Q positive	System <i>gains</i> heat
Q negative	System <i>loses</i> heat
W positive	Work done <i>by</i> system
W negative	Work done <i>on</i> system

The First Law of Thermodynamics

The internal energy of the system depends only on its temperature. The work done and the heat added, however, depend on the details of the process involved.



Quiz

The first Law of Thermodynamics, $\Delta U = Q - W$, means:

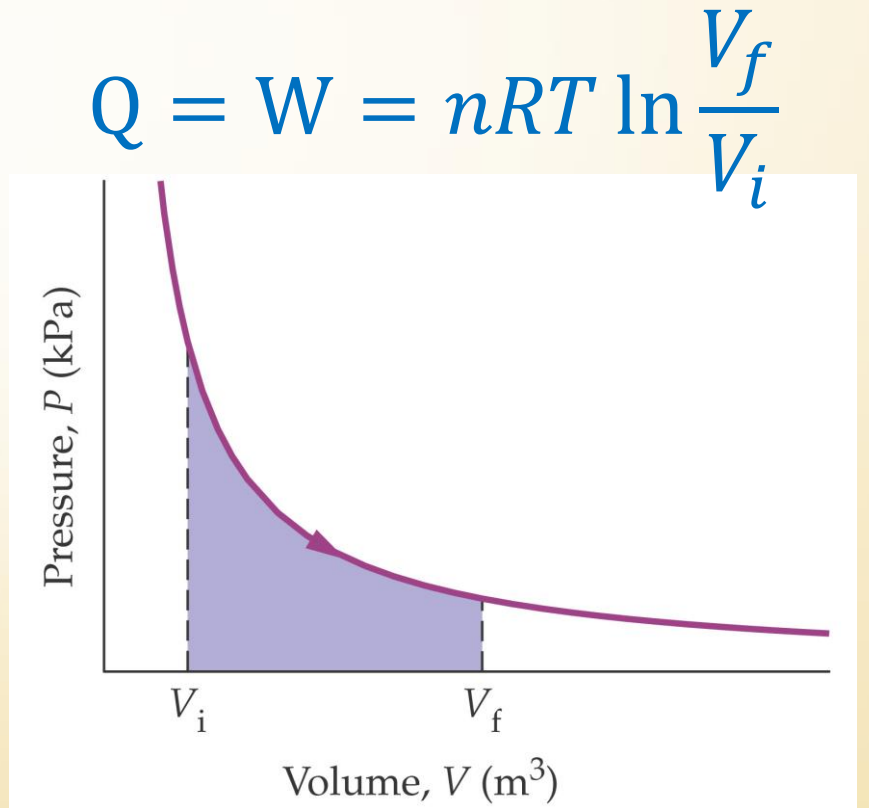
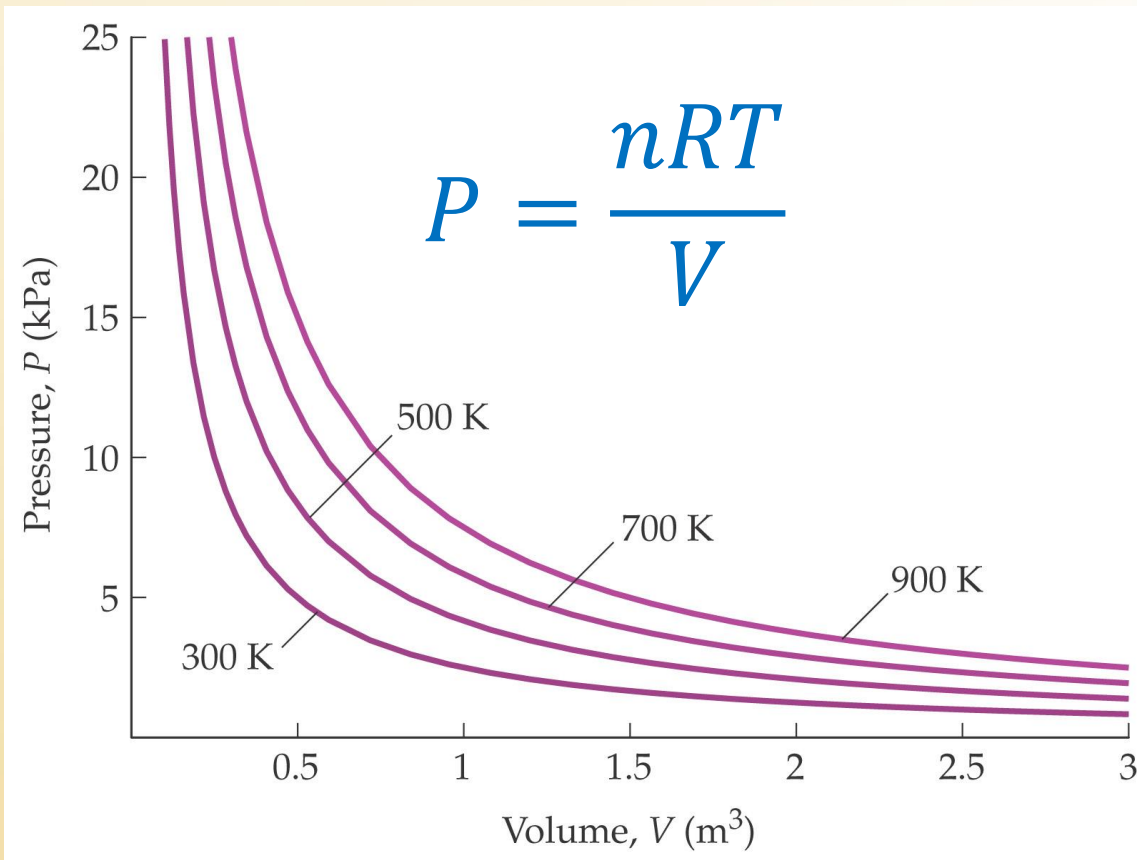
- A. Heat cannot be added to a system without work being done.
- B. Work cannot be done without heat being added.
- C. The amount of work done always equals the amount of heat added.
- D. The total internal energy of a system is conserved.

CHOOSE THE TRUE STATEMENT.

Processes in Thermodynamics

- Isothermal process → takes place at constant temperature
(*e.g. freezing of water to ice at 0°C*)
- Any heat flow into or out of the system must be slow enough to maintain thermal equilibrium
- For ideal gases, if ΔT is zero, $\Delta U = 0$
- Therefore, $Q = W$
 - Any energy entering the system (Q) must leave as work (W)

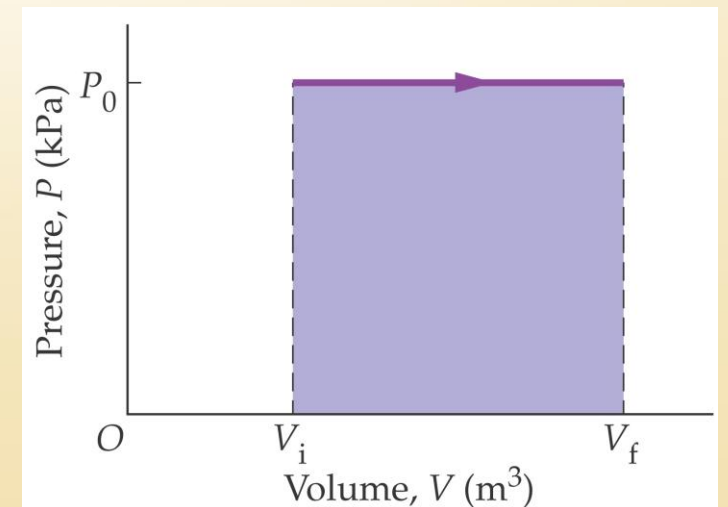
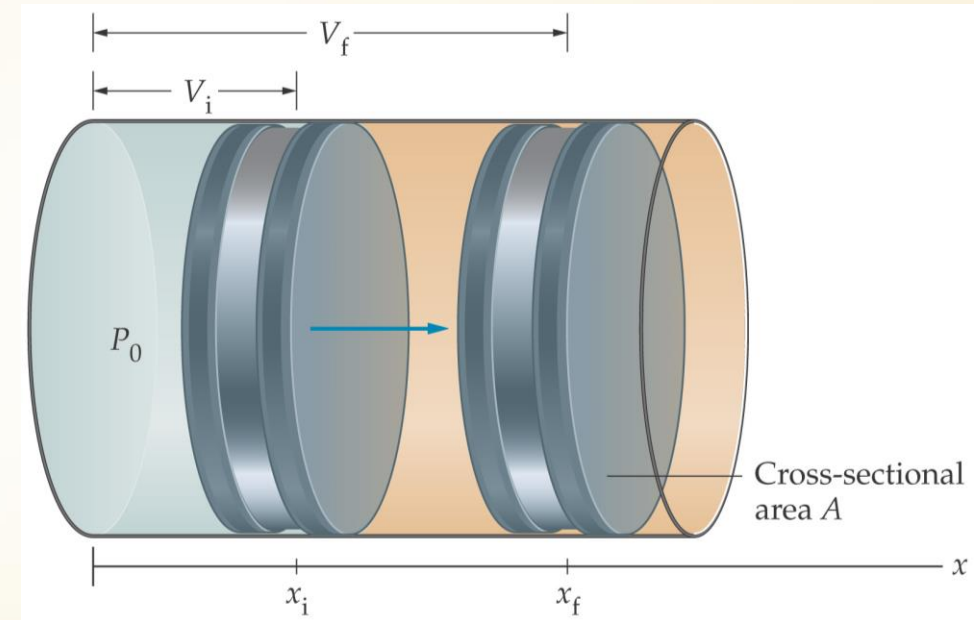
For an **ideal gas** undergoing an isothermal process, pressure varies inversely with volume.



Processes in Thermodynamics

- **Isobaric process** → takes place constant pressure
(e.g. heating of water in open air → under atmospheric pressure)
- ΔU , W , and Q are generally non-zero, but calculating the work done by an ideal gas is straightforward

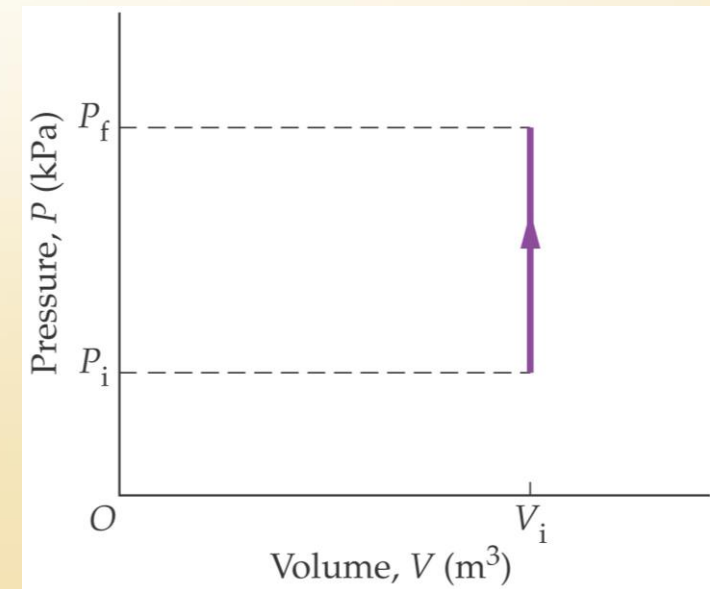
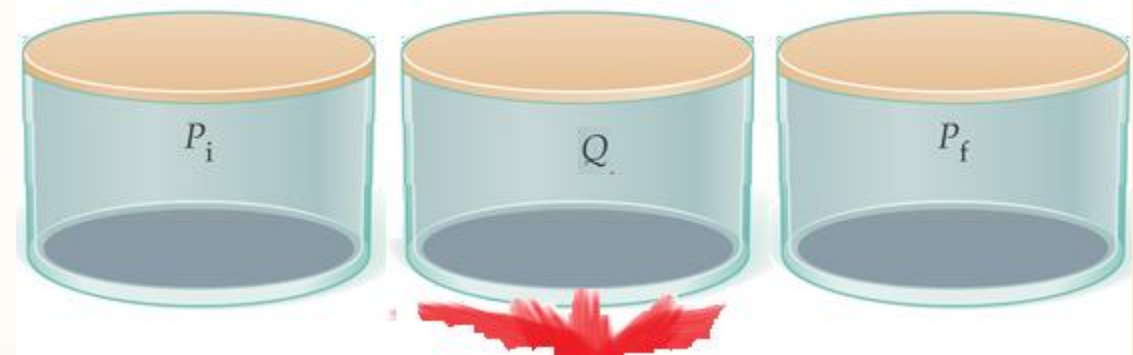
$$W = P\Delta V$$



Processes in Thermodynamics

- **Isochoric process** → takes place constant volume
(e.g. heating of gas in a sealed metal container)
- When the volume of a system doesn't change, it will do no work on its surroundings. $W = 0$

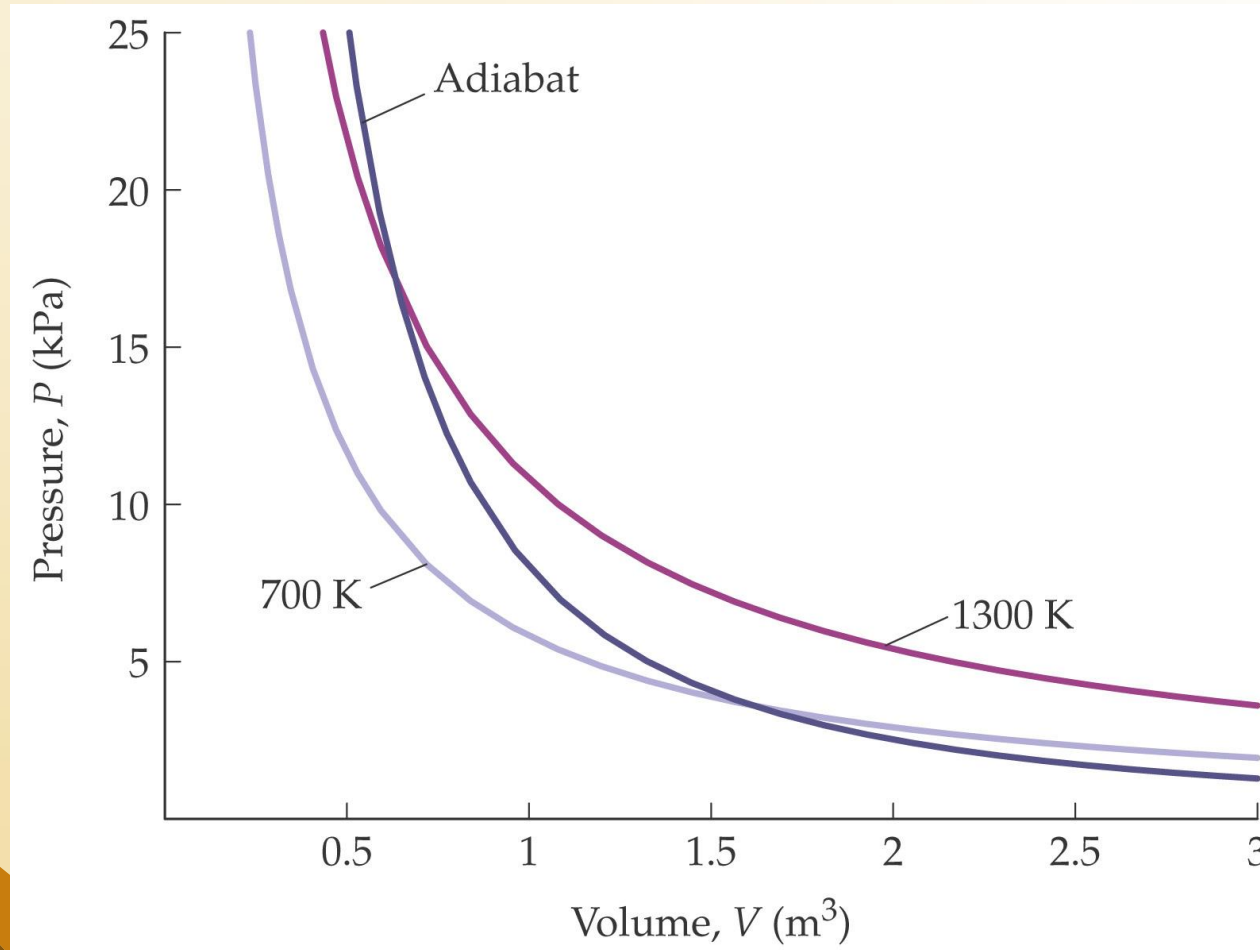
$$\Delta U = Q$$



Processes in Thermodynamics

- **Adiabatic process** $\rightarrow$ no heat is added to/removed from the system
- Therefore $Q = 0$ and $\Delta U = -W$
- When a system expands adiabatically, W is positive (the system does work) so ΔU is negative.
- When a system compresses adiabatically, W is negative (work is done on the system) so ΔU is positive.

Processes in Thermodynamics



- The adiabatic P - V curve is similar to the isothermal one, but is steeper.
- The P - V curve for an adiabat is given by

$$PV^\gamma = \text{constant}$$

- For the same volume change

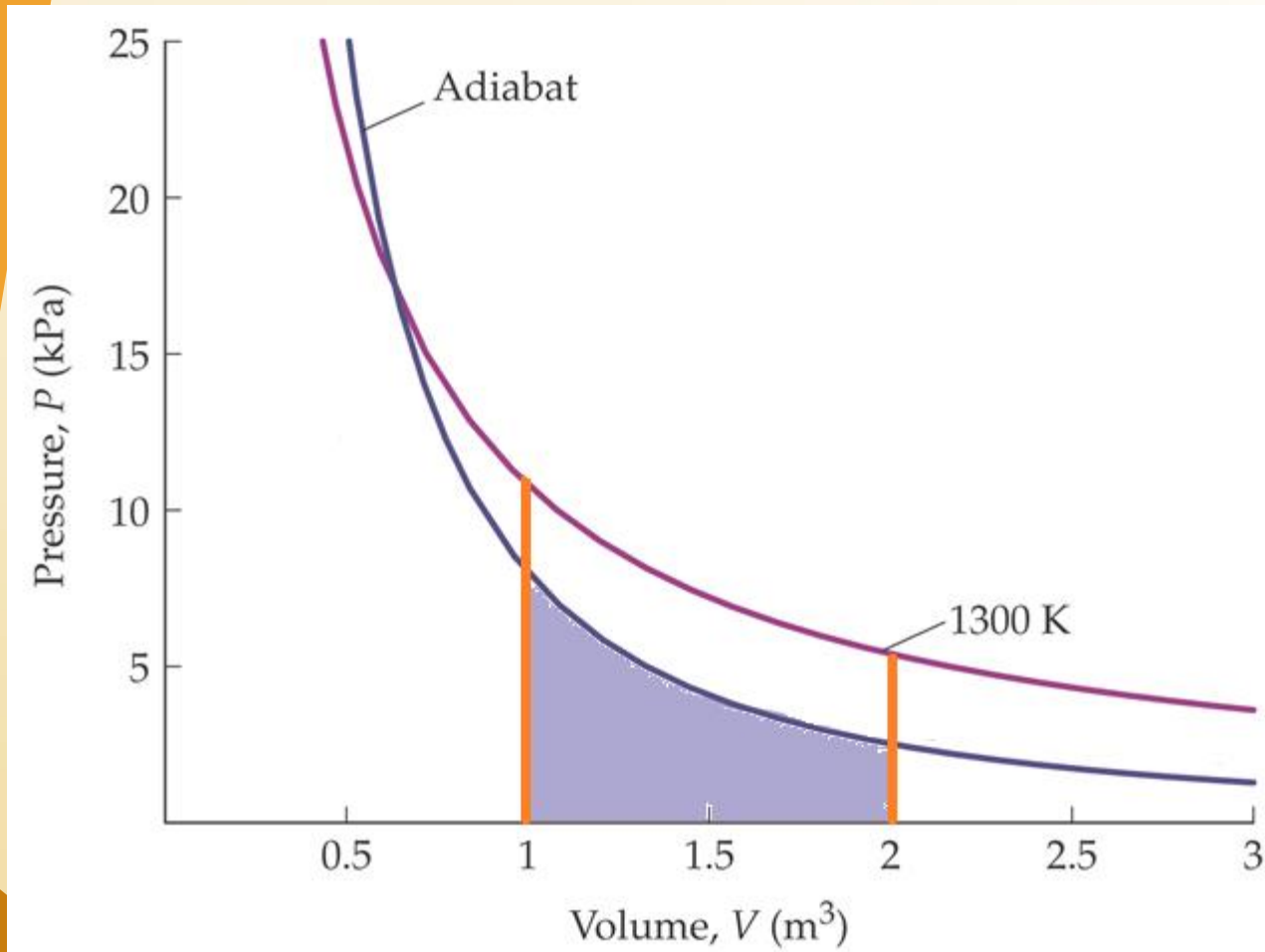
$$W_{adiabat} < W_{isotherm}$$

For an ideal gas:

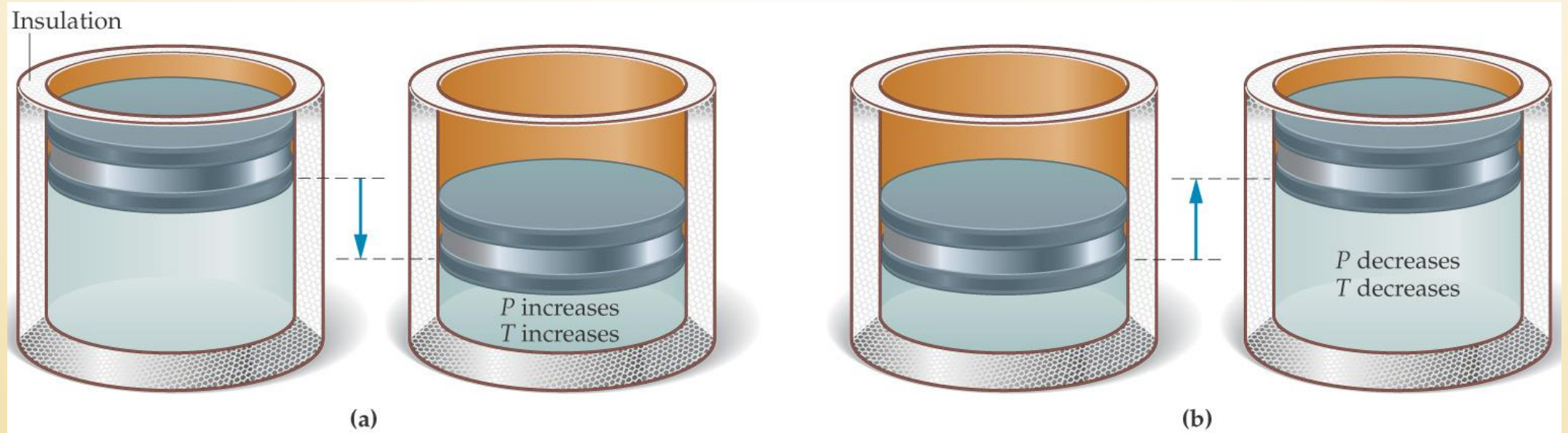
$$W_{adiab} = C_V(T_2 - T_1)$$

Or

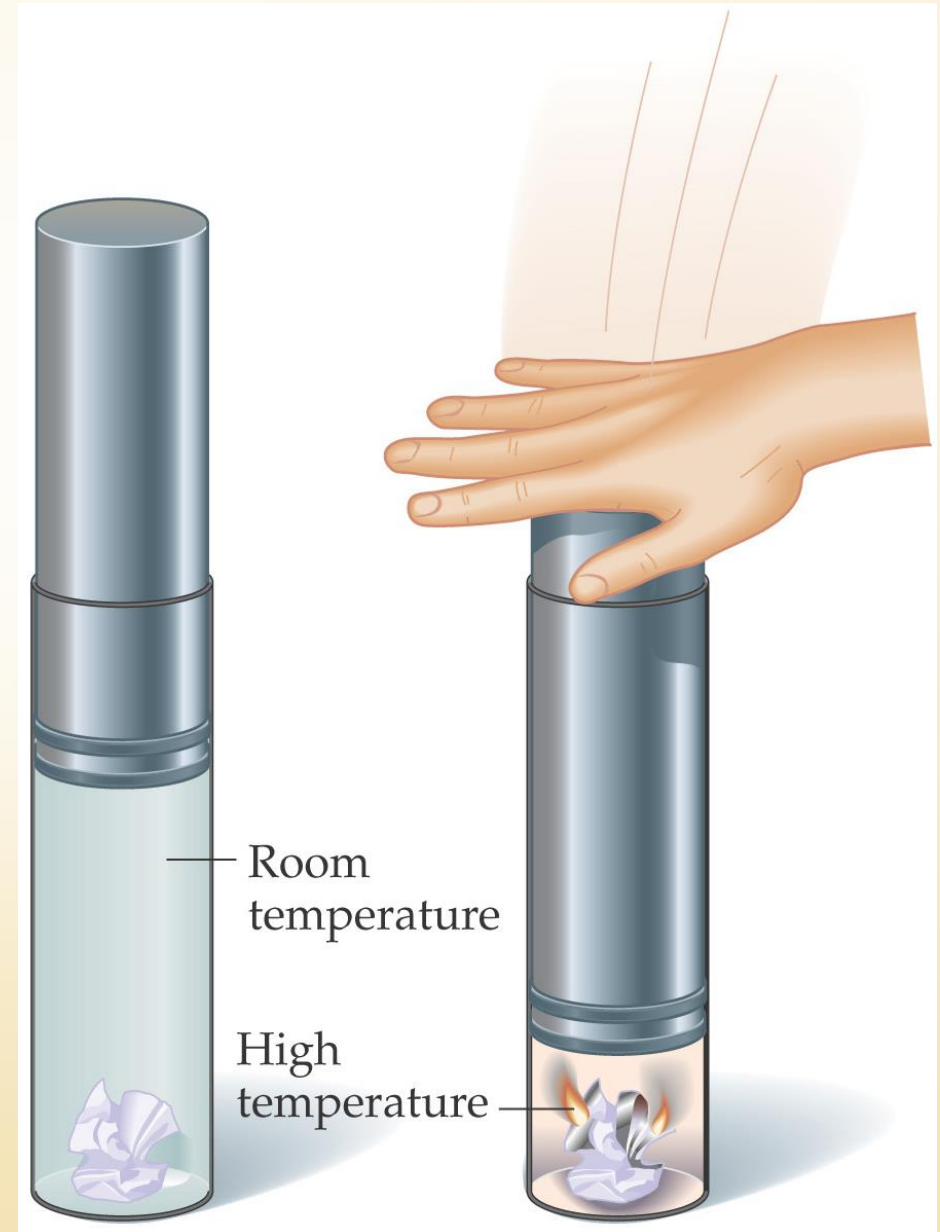
$$W_{adiabat} = \frac{P_2V_2 - P_1V_1}{\gamma - 1}$$



One way to ensure that a process is adiabatic is to insulate the system.



Another way to ensure that a process is effectively adiabatic is to have the volume change occur so **quickly** that heat has no time to flow in or out of the system.



In summary:

TABLE 18–2 Thermodynamic Processes and Their Characteristics

Constant pressure	$W = P\Delta V$	$Q = \Delta U + P\Delta V$
Constant volume	$W = 0$	$Q = \Delta U$
Isothermal (constant temperature)	$W = Q$	$\Delta U = 0$
Adiabatic (no heat flow)	$W = -\Delta U$	$Q = 0$

Copyright © 2007 Pearson Prentice Hall, Inc.

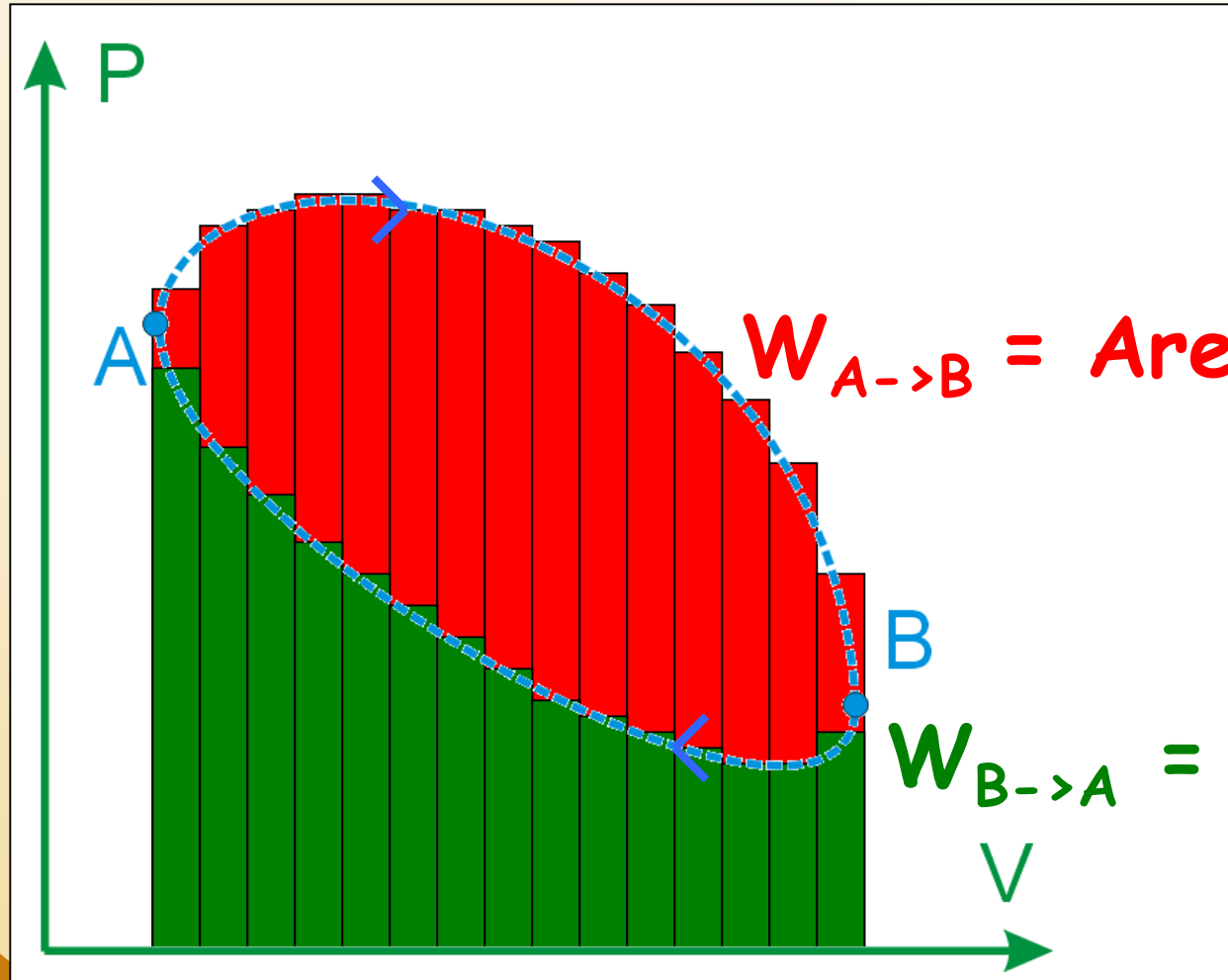
Other Processes in Thermodynamics

- Reversible process $\rightarrow$ system is close to equilibrium at all times
- Cyclic process $\rightarrow$ the final and initial state are the same.

For the ideal gas, $\Delta U = 0$ and $Q = W$

Consider cycle $A \rightarrow B \rightarrow A$

(work done by gas in a cycle)

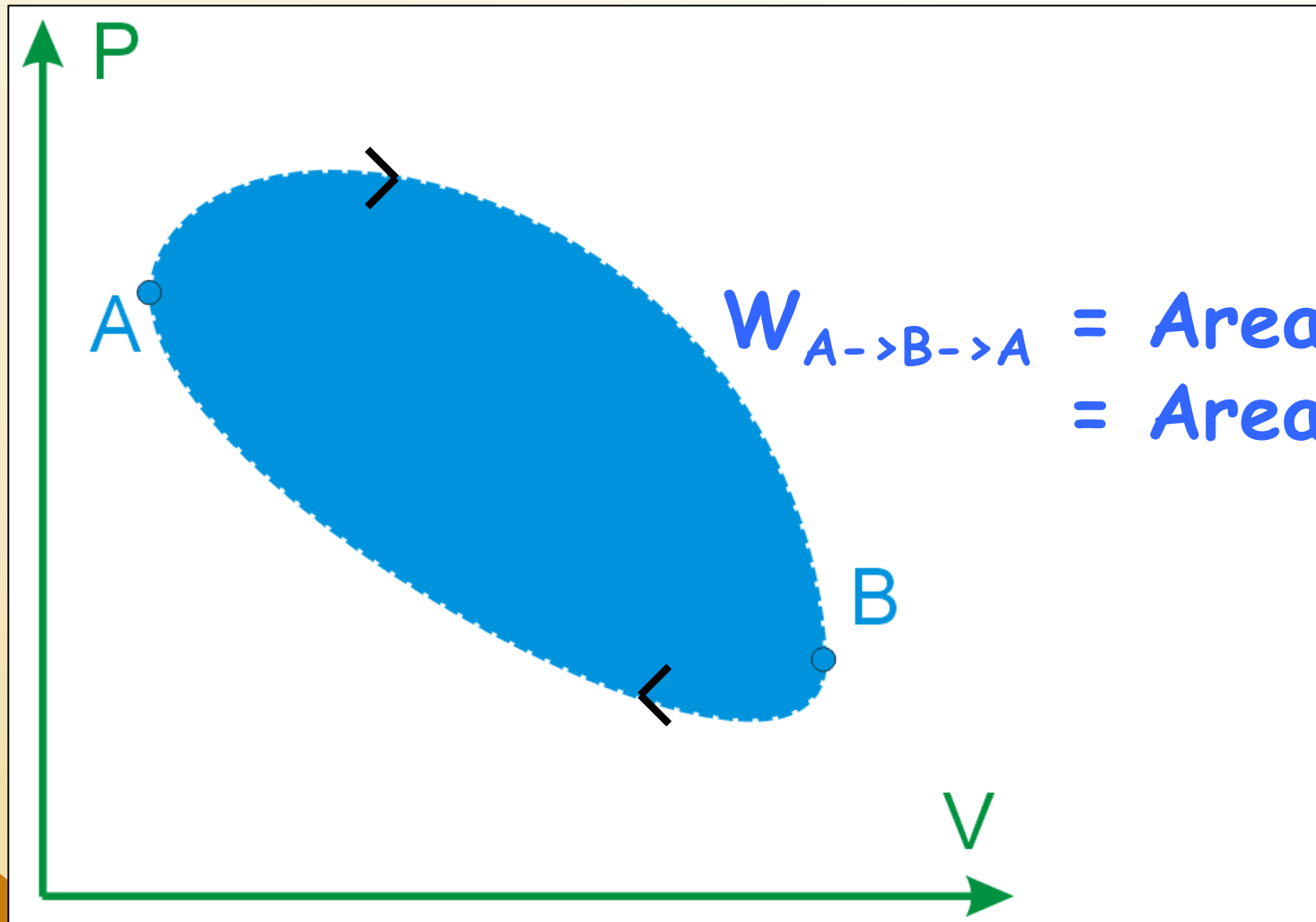


$$W_{A \rightarrow B} = \text{Area 1}$$

$$W_{B \rightarrow A} = - \text{Area 2}$$

Consider cycle $A \rightarrow B \rightarrow A$

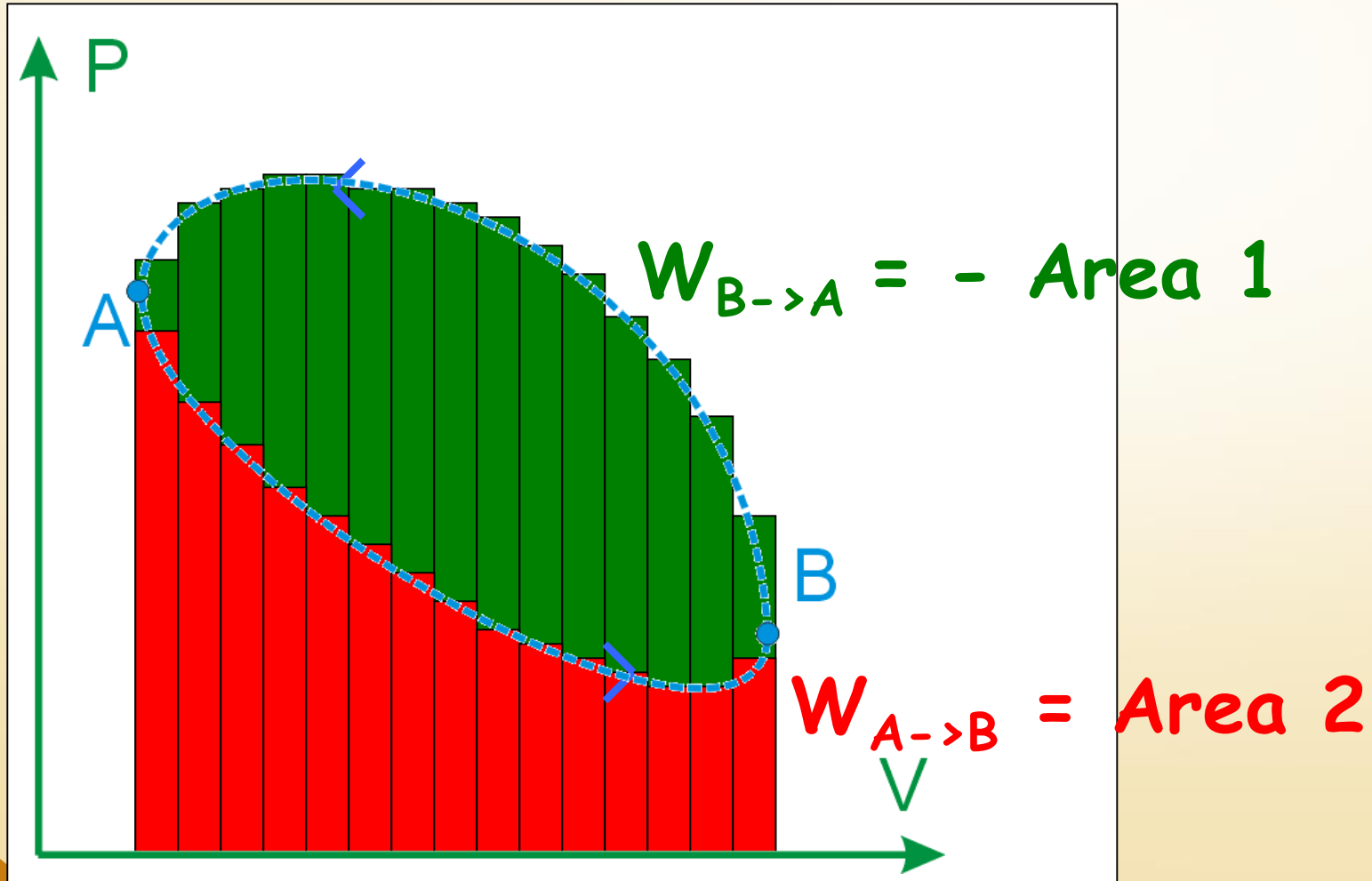
(work done by gas in a cycle)



$$W_{A \rightarrow B \rightarrow A} = \text{Area 1} - \text{Area 2} \\ = \text{Area of loop}$$

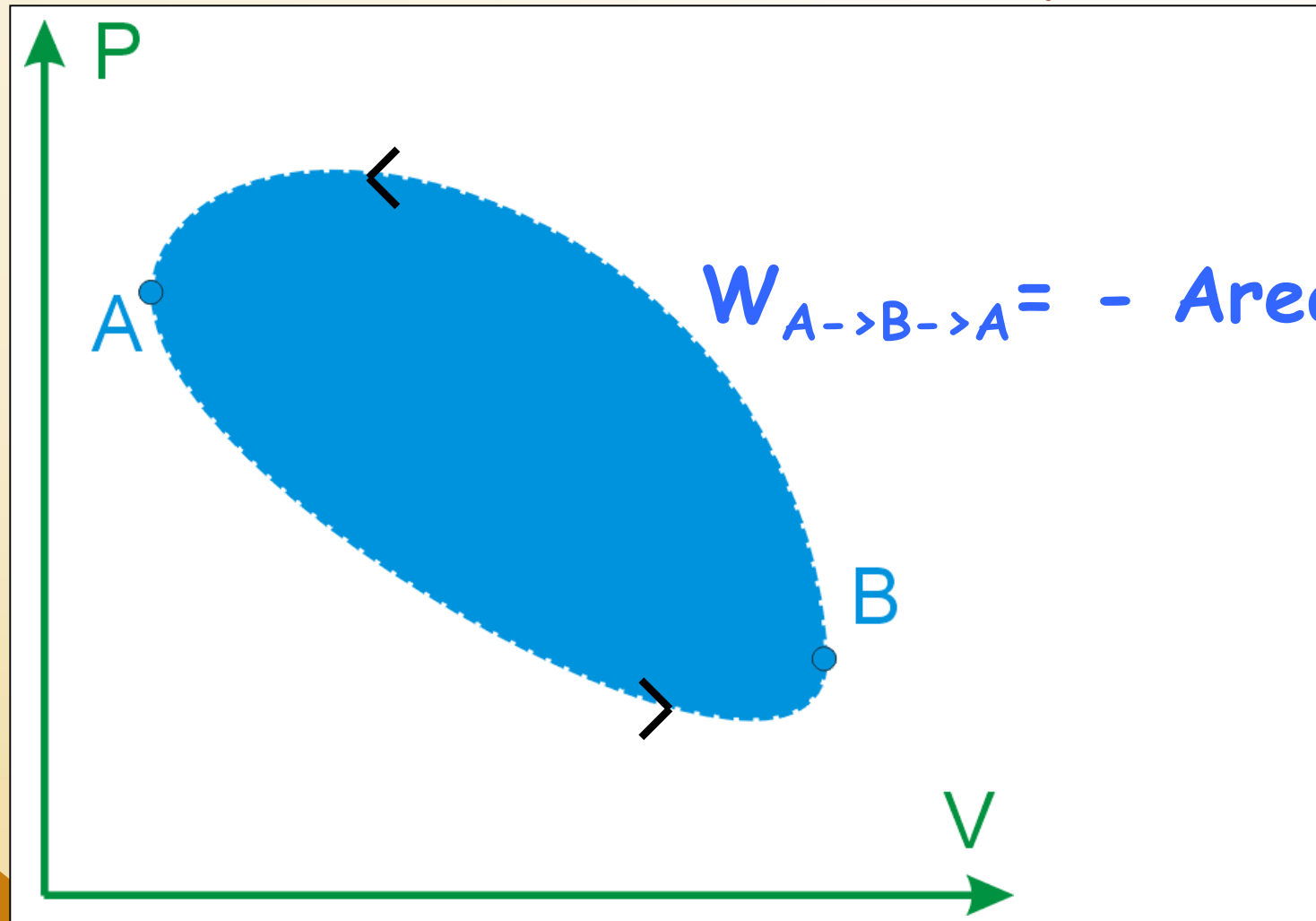
Reverse the cycle, make it counter clockwise

(work done by gas in a cycle)



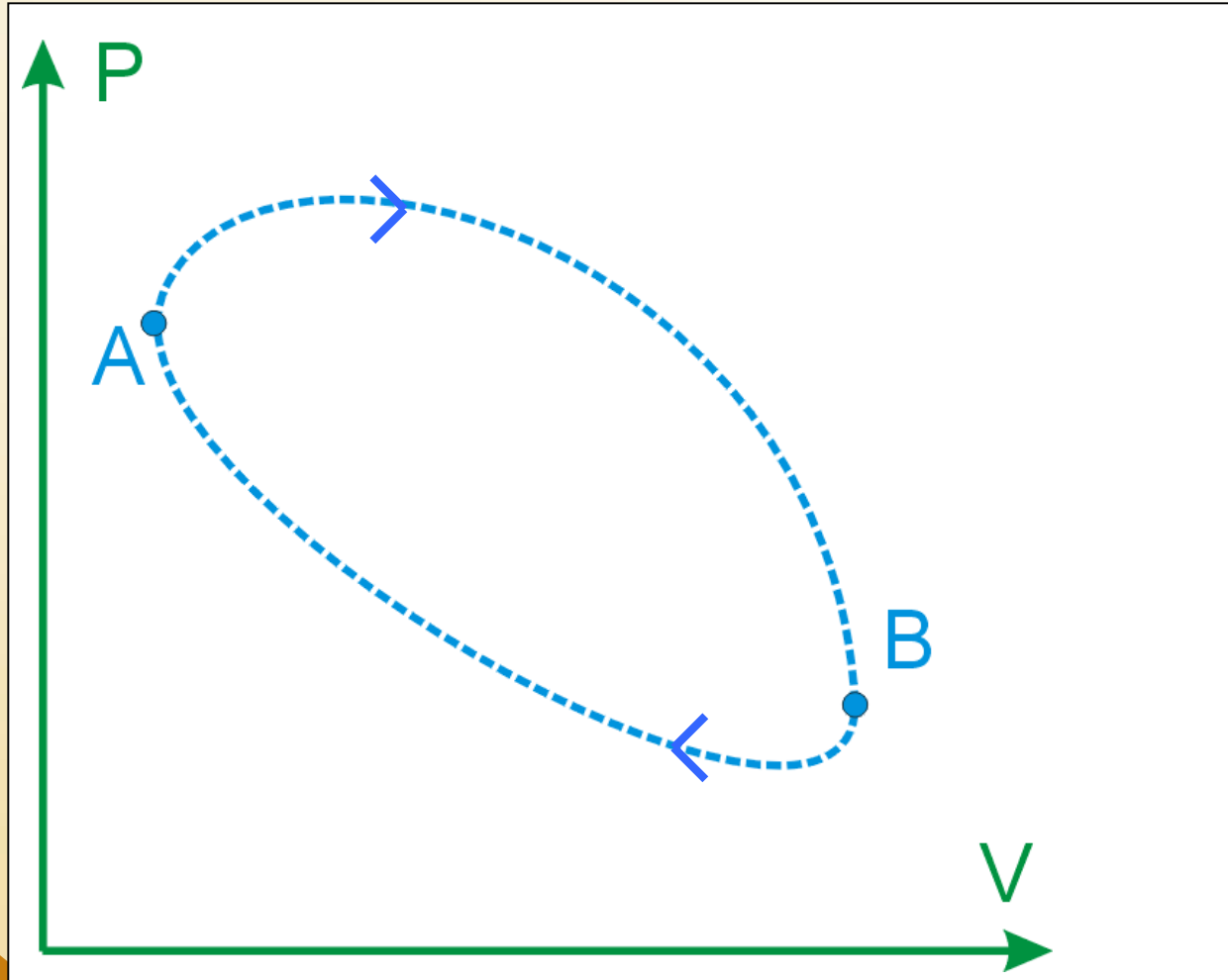
Reverse the cycle, make it counter clockwise

(work done by gas in a cycle)



$$W_{A \rightarrow B \rightarrow A} = - \text{Area of loop}$$

Internal Energy in closed cycles



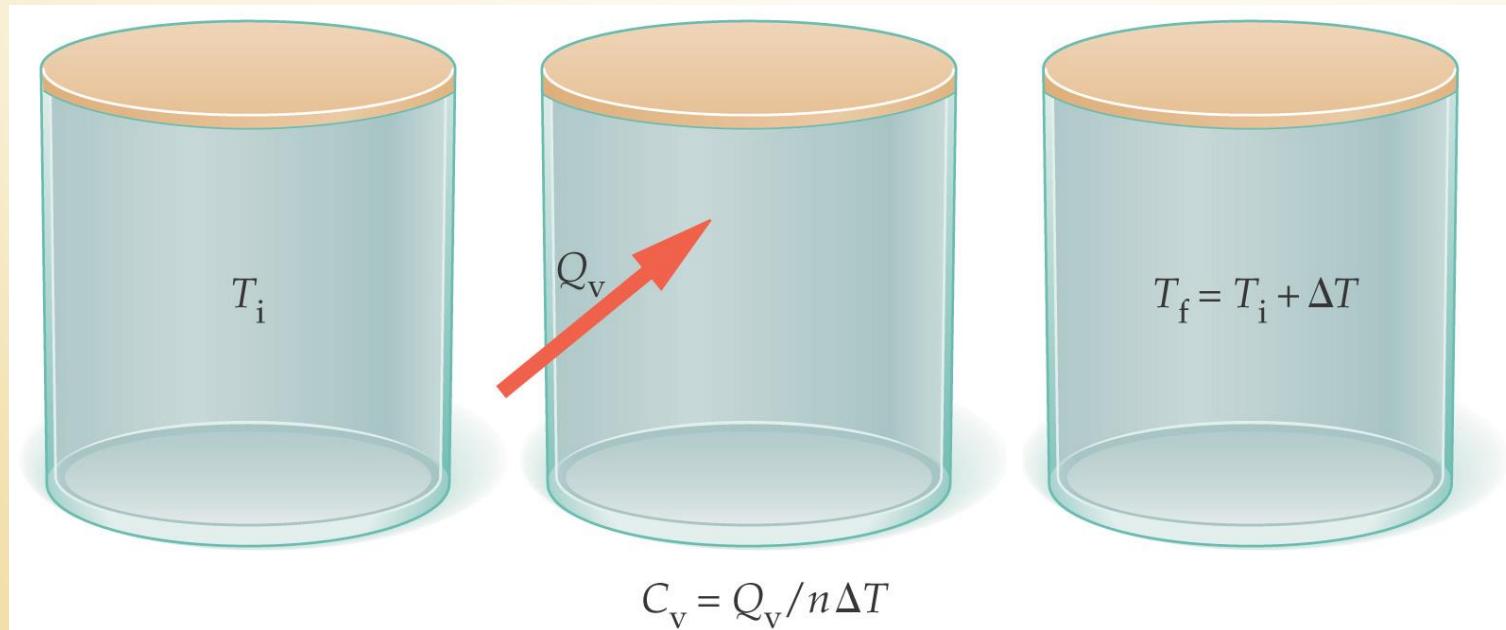
$\Delta U=0$
in closed cycles

Specific Heats for an Ideal Gas

Specific heats for ideal gases must be quoted either at constant pressure or at constant volume.

For a constant-volume process,

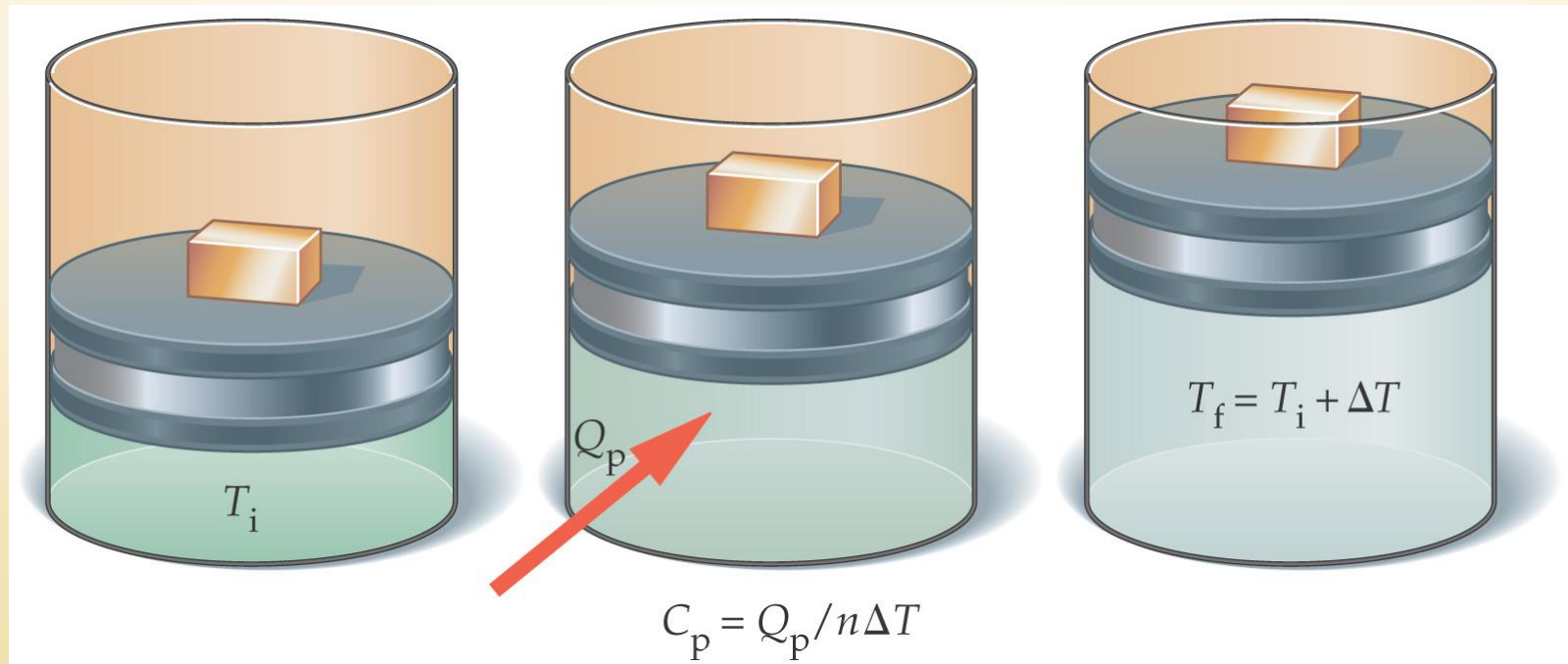
$$Q_v = nC_v\Delta T$$



Specific Heats for an Ideal Gas

At constant pressure,

$$Q_p = nC_p \Delta T$$



Specific Heats for an Ideal Gas

Both C_V and C_p can be calculated for a monatomic ideal gas using the first law of thermodynamics.

$$C_V = \frac{3}{2}R$$

$$C_p = \frac{5}{2}R$$

$$C_p - C_V = R$$

$$\gamma = \frac{C_p}{C_V} = \frac{\frac{5}{2}R}{\frac{3}{2}R} = \frac{5}{3}$$

Specific Heats for an Ideal Gas

Although this calculation was done for an ideal, monatomic gas, it works well for real gases.

TABLE 18–3 $C_p - C_v$ for Various Gases

Helium	$0.995 R$
Nitrogen	$1.00 R$
Oxygen	$1.00 R$
Argon	$1.01 R$
Carbon dioxide	$1.01 R$
Methane	$1.01 R$

Calculating Energy Transfer

Calculate the energy transferred when a block of aluminum at 80.0°C is placed in 1.00 liter (1kg) of water at 25.0°C if the final temperature becomes 30.0°C .

Step 1. List all known values

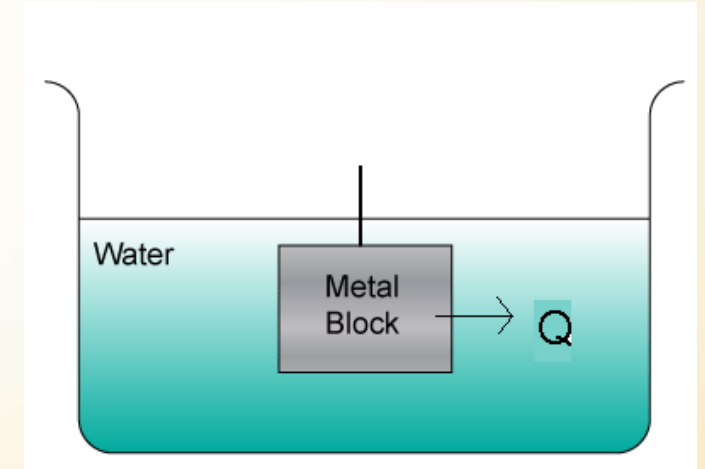
Mass of water = 1 kg

C_p of water = $4184 \text{ J/kg}^{\circ}\text{C}$

Difference in temperature = $\Delta T = 30.0^{\circ}\text{C} - 25.0^{\circ}\text{C} = 5.0^{\circ}\text{C}$

C_p of Al = $900 \text{ J/kg}^{\circ}\text{C}$

Difference in temperature = $\Delta T = 80.0^{\circ}\text{C} - 30.0^{\circ}\text{C} = 50.0^{\circ}\text{C}$

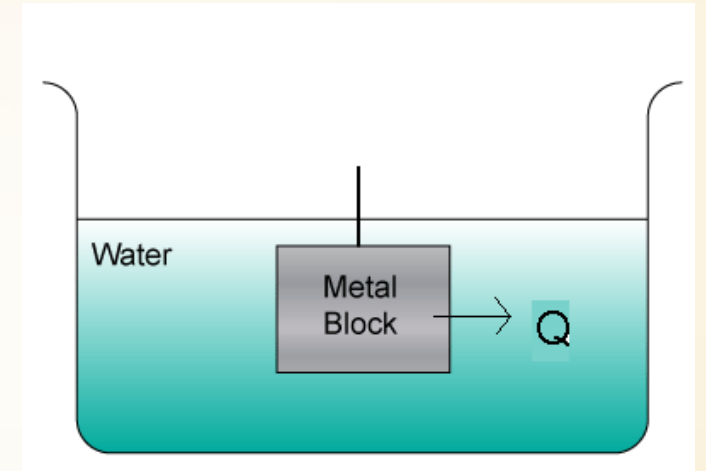


Calculating Energy Transfer

Step 2. List all unknown values

$Q = \text{energy transferred}$

$m_{Al} = \text{mass of the Al block}$



Step 3. Select equations to solve unknown values

$$Q = mC_p\Delta T$$

$$Q_{Al} = Q_{water}$$

Step 4. Solve for Q_{water}

$$Q_{water} = (1.00\text{kg}) \times 4184\text{ J/kg } ^\circ\text{C} \times 5.0^\circ\text{C} = 20,920\text{ J gained}$$

Calculating Energy Transfer

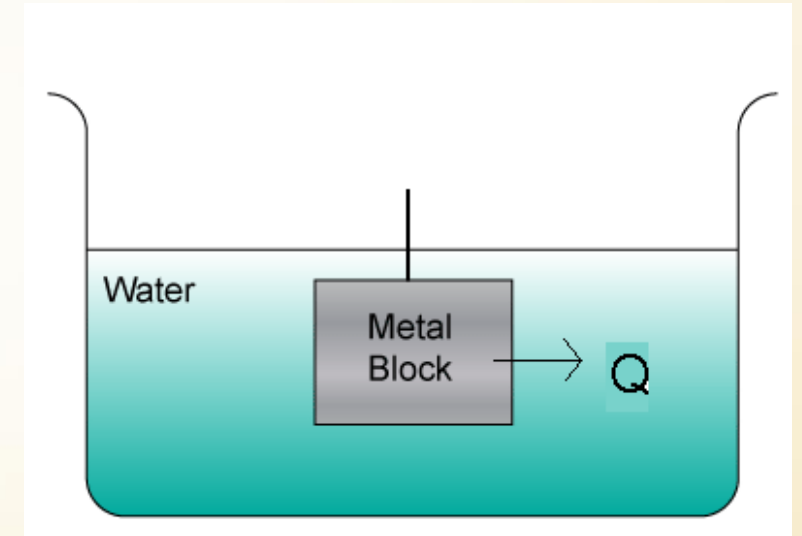
Step 5. Solve for m_{Al}

$$Q_{Al} \text{ (lost)} = Q_{\text{water}} \text{ (gained)} = 20,920 \text{ J}$$

$$Q_{Al} = m_{Al} C_p \Delta T$$

$$m_{Al} = \frac{Q_{Al}}{C_p \Delta T} = \frac{20920 \text{ J}}{900 \text{ J/kg } ^\circ\text{C} \times 50.0^\circ\text{C}}$$

$$m_{Al} = 0.465 \text{ kg} = 465 \text{ g}$$





Examples and Quizzes

A cylinder of radius 5 cm is kept at a pressure with a piston of mass 75 kg.

a) What is the pressure inside the cylinder?

$1.950 \times 10^5 \text{ Pa}$

b) If the gas expands such that the cylinder rises 12.0 cm, what work was done by the gas?

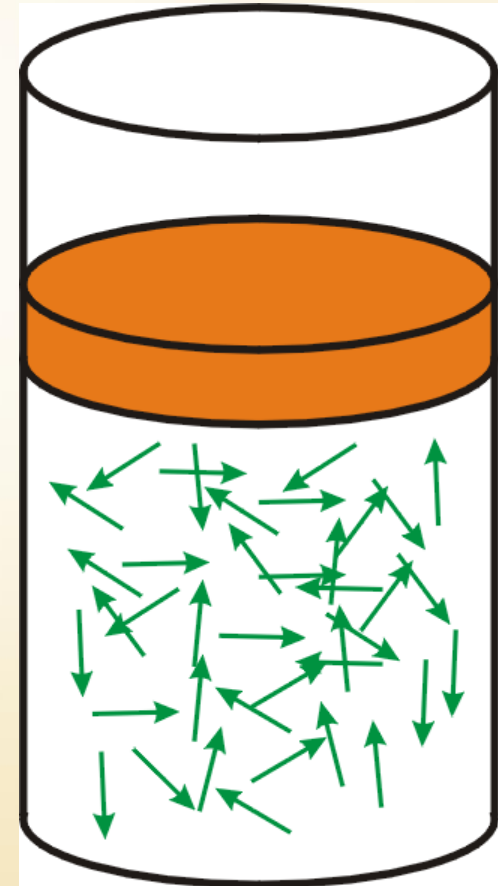
183.8 J

c) What amount of the work went into changing the gravitational PE of the piston?

88.3 J

d) Where did the rest of the work go?

Compressing the outside air

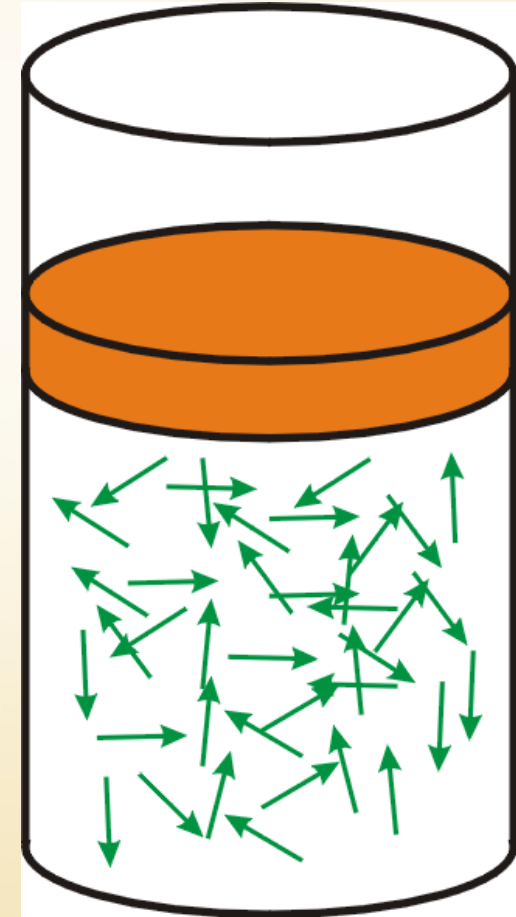


A massive copper piston traps an ideal gas as shown to the right. The piston is allowed to freely slide up and down and equilibrate with the outside air.

The pressure inside the cylinder is _____ the pressure outside.

The temperature inside the cylinder is _____ the temperature outside.

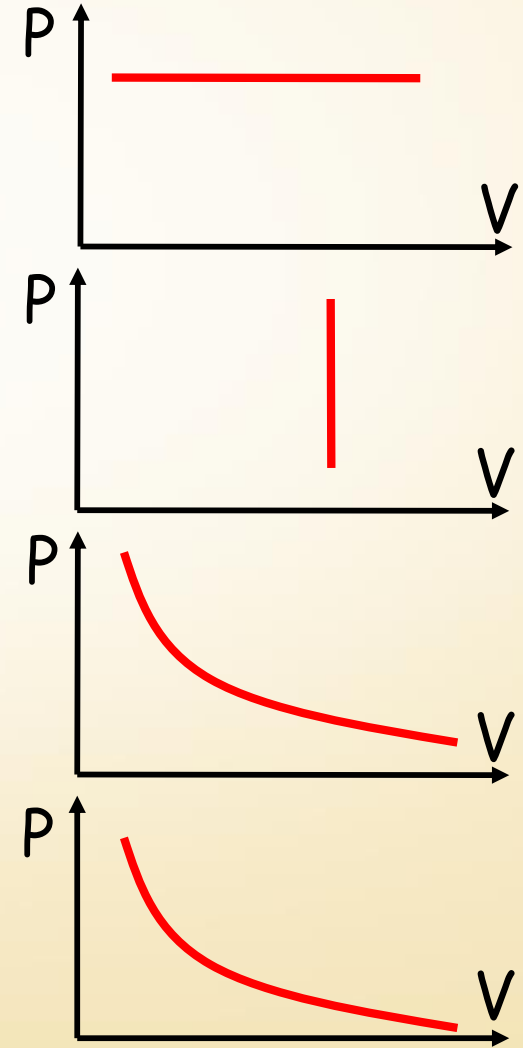
If the gas is heated by a steady flame, and the piston rises to a new equilibrium position, the new pressure will be _____ than the previous pressure.



- a) Greater than
- b) Less than
- c) Equal to

Identify the processes

- **Isobaric**
 - $P = \text{constant}$
- **Isochoric**
 - $V = \text{constant}$
 - $W = 0$
- **Isothermal**
 - $T = \text{constant}$
 - $\Delta U = 0$ (ideal gas)
- **Adiabatic**
 - $Q = 0$

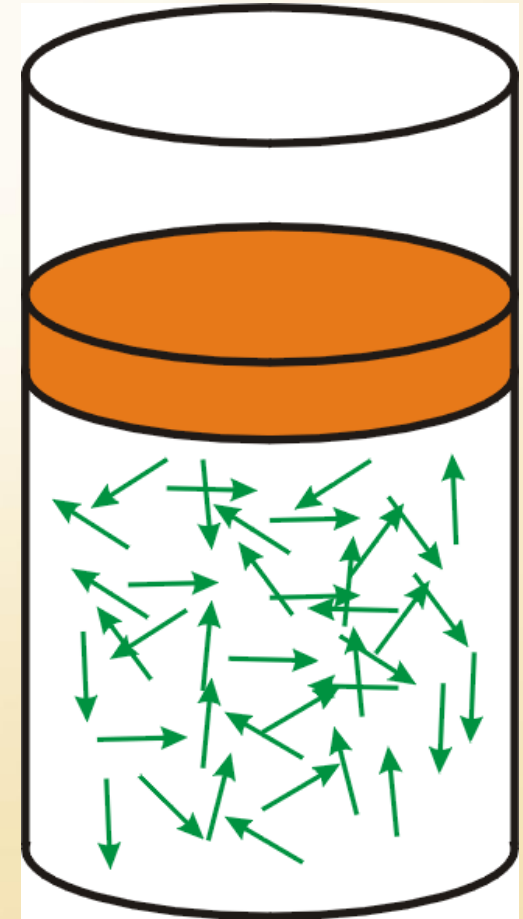


A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (state a). Weight is slowly added to the piston, *isothermally* compressing the gas to half its original volume (state b).

P_b is _____ P_a
 T_b is _____ T_a
 W_{ab} is _____ 0
 U_b is _____ U_a
 Q_{ab} is _____ 0

- a) Greater than
- b) Less than
- c) Equal to

Outside Air:
Room T , Atm. P

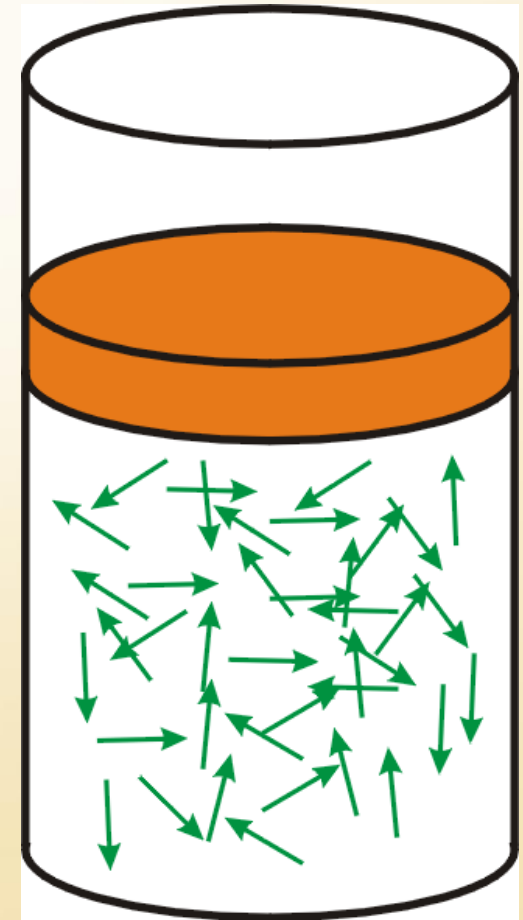


A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (state a). Weight is slowly added to the piston, *adiabatically* compressing the gas to half its original volume (state b).

P_b is _____ P_a
 T_b is _____ T_a
 W_{ab} is _____ 0
 U_b is _____ U_a
 Q_{ab} is _____ 0

- a) Greater than
- b) Less than
- c) Equal to

Outside Air:
Room T , Atm. P

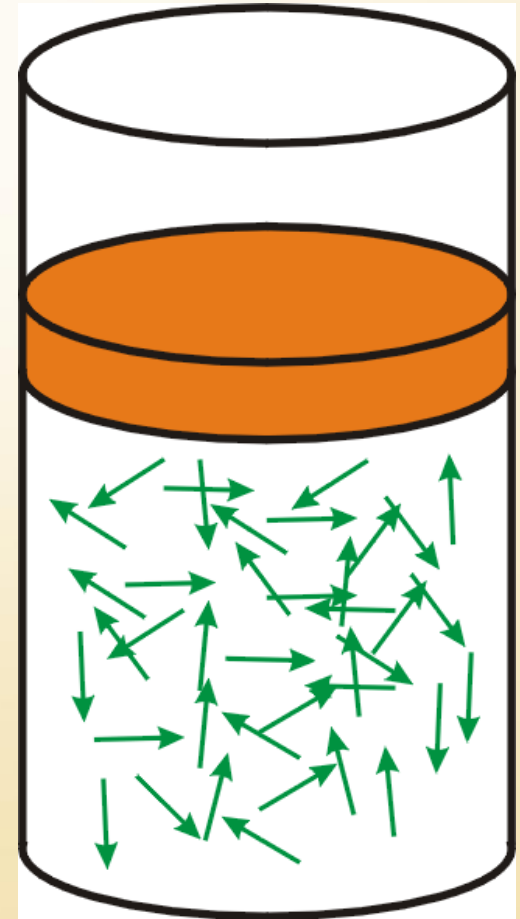


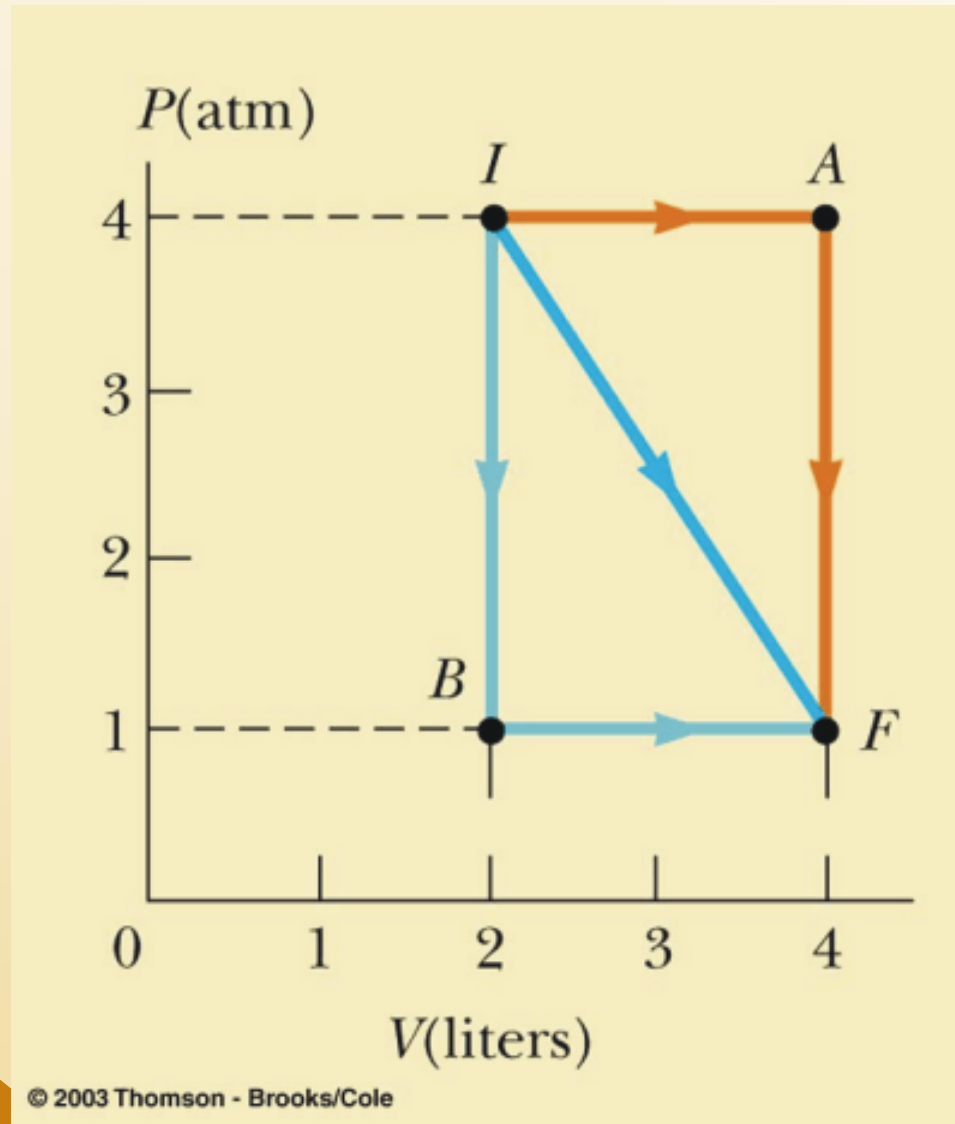
A massive piston traps an amount of Helium gas as shown. The piston freely slides up and down. The system initially equilibrates at room temperature (state a). The gas is cooled, *isobarically* compressing the gas to half its original volume (state b).

P_b is _____	P_a
T_b is _____	T_a
W_{ab} is _____	0
U_b is _____	U_a
Q_{ab} is _____	0

- a) Greater than
- b) Less than
- c) Equal to

Outside Air:
Room T , Atm. P





a) What amount of work is performed by the gas in the cycle IAFI?

$$W = 304 \text{ J}$$

b) How much heat was inserted into the gas in the cycle IAFI?

$$Q = 304 \text{ J}$$

c) What amount of work is performed by the gas in the cycle IBFI?

$$W = -304 \text{ J}$$

Consider a monotonic ideal gas.

a) What work was done by the gas from A to B?

20,000 J

b) What heat was added to the gas between A and B?

20,000

c) What work was done by the gas from B to C?

-10,000 J

d) What heat was added to the gas between B and C?

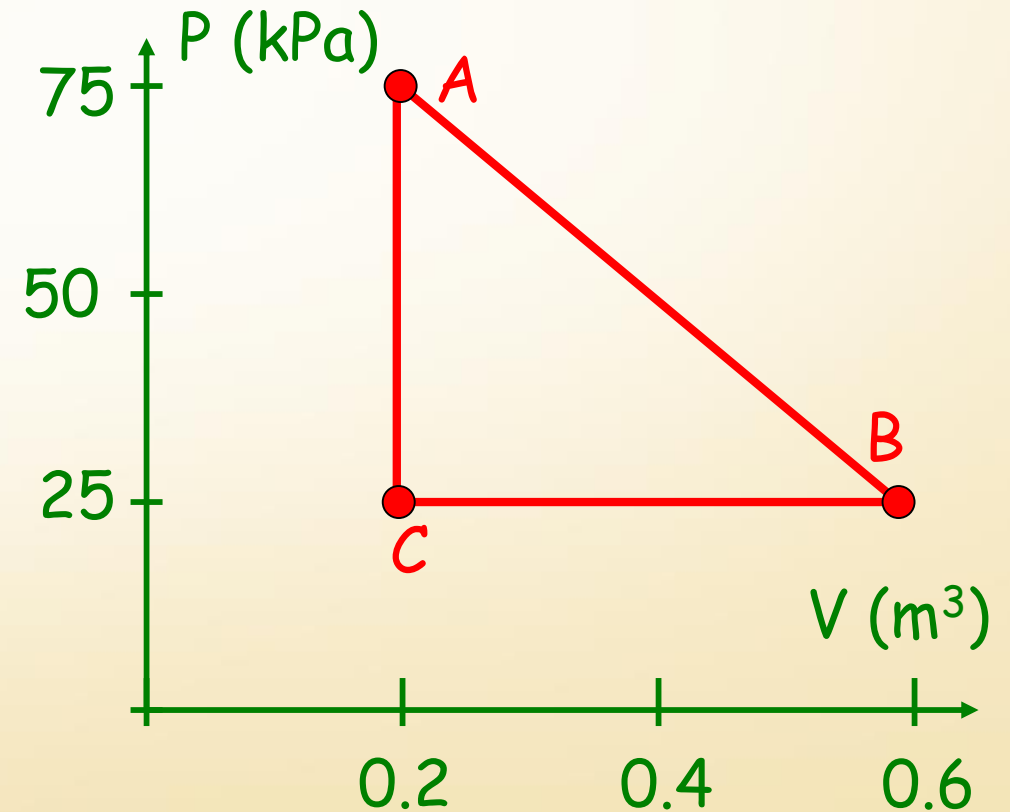
-25,000 J

e) What work was done by the gas from C to A?

0

f) What heat was added to the gas from C to A?

15,000 J



Take solutions from last problem and find:

- a) Net work done by gas in the cycle
- b) Amount of heat added to gas

$$W_{AB} + W_{BC} + W_{CA} = 10,000 \text{ J}$$

$$Q_{AB} + Q_{BC} + Q_{CA} = 10,000 \text{ J}$$

Consider an ideal gas undergoing the path through the PV diagram.
In going from A to B to C,

(a) the work done BY the gas is _____ 0.

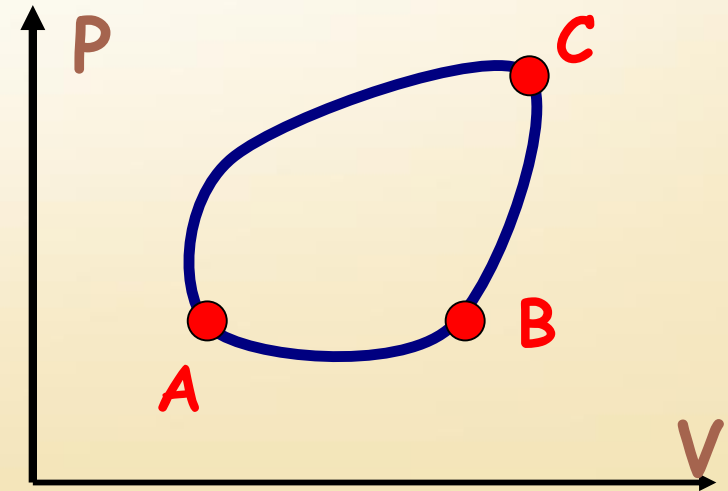
(b) the change of the internal energy of the gas is _____ 0.

(c) the amount of heat added to the gas is _____ 0.

a) >

b) <

c) =



In going from A to B to C to D to A,

(a) the work done BY the gas is _____ 0.

(b) the change of the internal energy of the gas is _____ 0.

(c) the heat added to the gas is _____ 0.

a) >

b) <

c) =

