Heat Transfer Mechanisms; Specific Heats, Adiabatic Processes; Equipartition Theorem

Knight Ch. 19.8, 19.7; Most of Ch. 20 (most important: 20.3-20.4)

Physics 2C, Spring 2025

Agenda Today (April 28 and 29, 2025)

- 3 Heat Transfer Mechanisms
- Molar Heat Capacity at const. p vs. const. V
- Adiabatic Processes, Adiabatic Constant
- Microscopic Description
  - Equipartition Theorem
  - C_V vs. T for diatomic molecules

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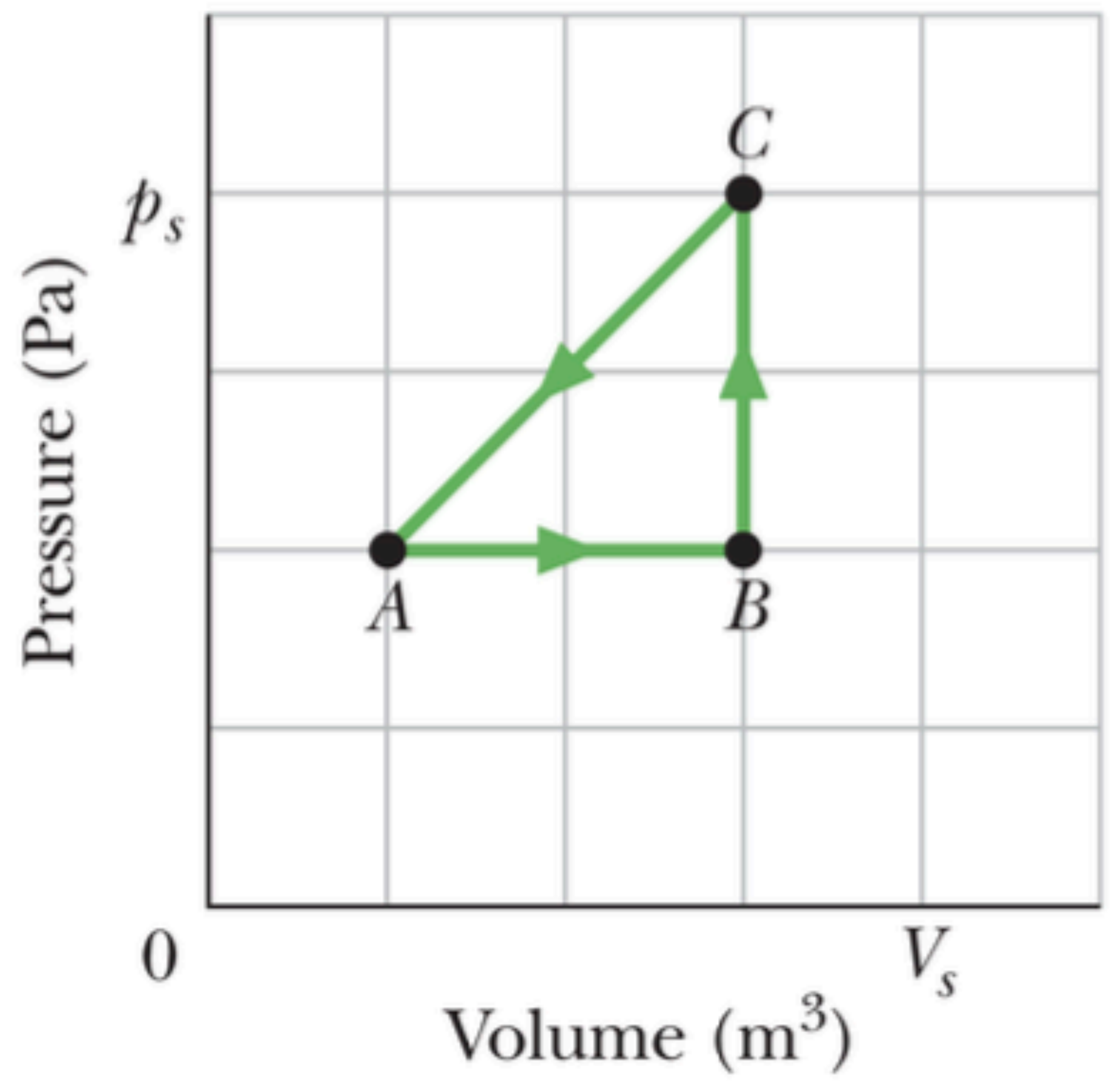
Clicker/Poll Question (Review)

After filling in the following, how many minus signs are in the table? (W = work on gas)

A. 1
B. 2
C. 3
D. 4
E. 5



	Q	W	ΔE_{int}
$A \longrightarrow B$			+
$B \longrightarrow C$	+		
$C \longrightarrow A$			

Heat Transfer Mechanism #1: Conduction

Heat by touching. Power: $P_{\text{cond}} = \dfrac{dQ}{dt} = kA\dfrac{\Delta T}{\Delta x}$

FIGURE 19.22 Conduction of heat through a solid.

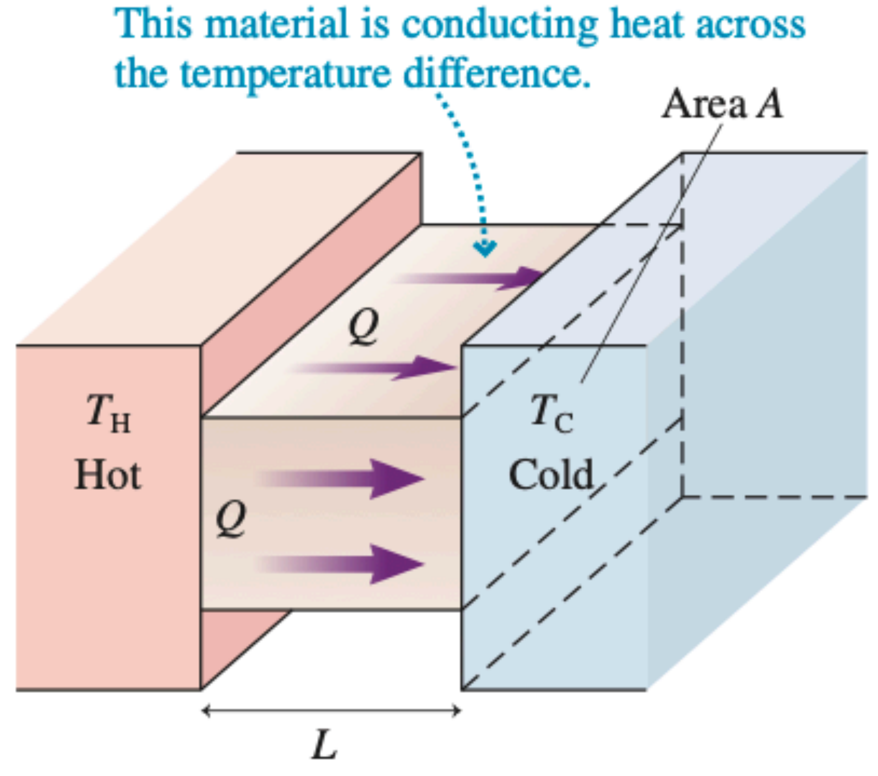


TABLE 19.5 Thermal conductivities

Material	k (W/m K)
Diamond	2000
Silver	430
Copper	400
Aluminum	240
Iron	80
Stainless steel	14
Ice	1.7
Concrete	0.8
Glass	0.8
Styrofoam	0.035
Air (20°C, 1 atm)	0.023

Clicker/Poll Question

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Estimate the power of heat loss via thermal conduction through a single-pane window on a chilly night in San Diego. Use $k_{\text{glass}} = 0.8\text{W}/(\text{K}\cdot\text{m})$; all other quantities, estimate yourself.

A. 2000 W
B. 300 W
C. 40 W
D. 5 W

Clicker/Poll Question

The above composite slab is made up of two different materials of the same dimensions. The left end has been touching a very hot thermal reservoir at high temperature the right end is touching a cold one. Which of the following is/are true statements regarding this situation?

A. The rate of energy flowing through the gold slab is the same as through the blue one.

B. $T_H - T_M = T_M - T_C$.

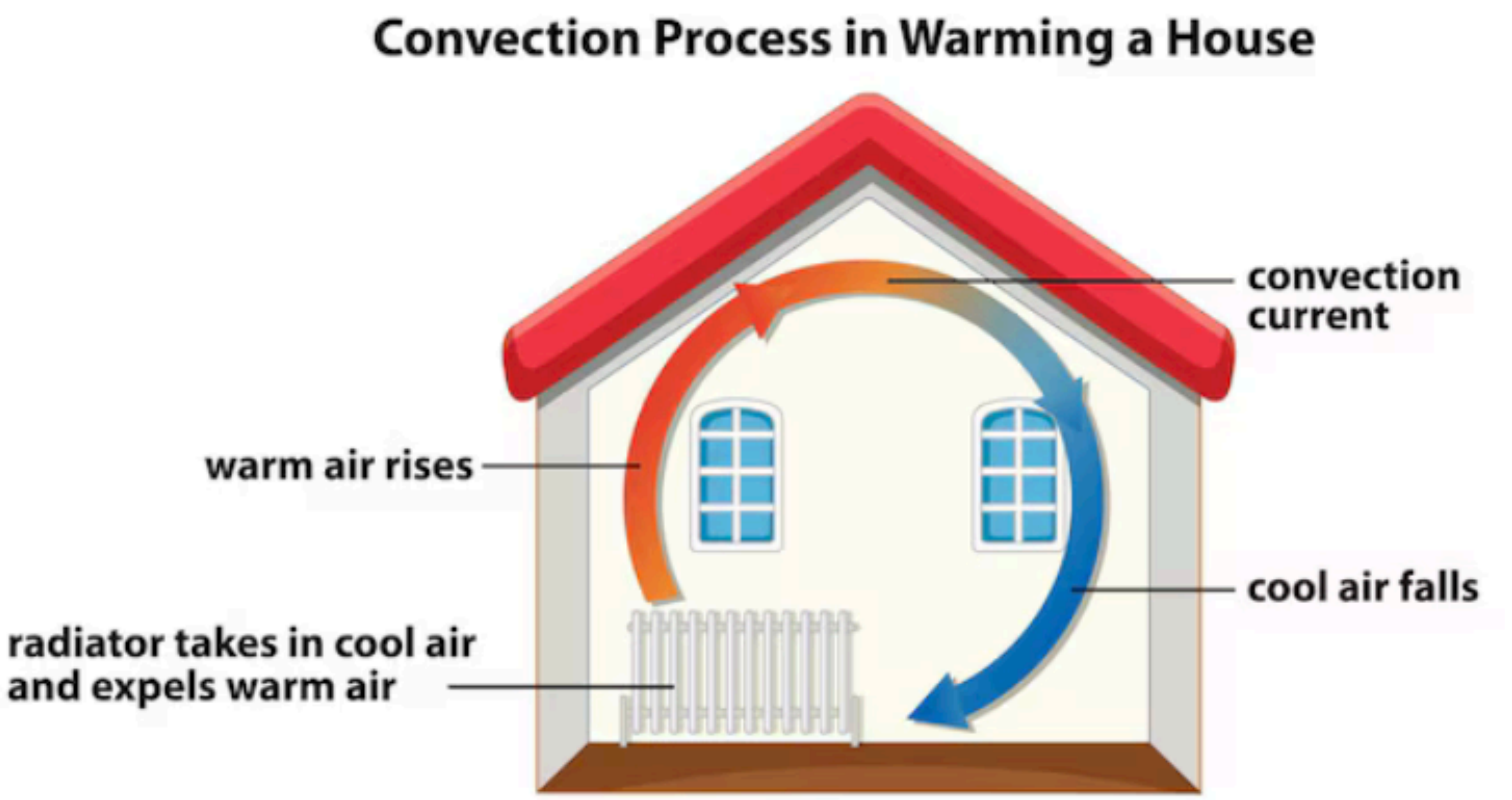
C. Both of the above are true statements.

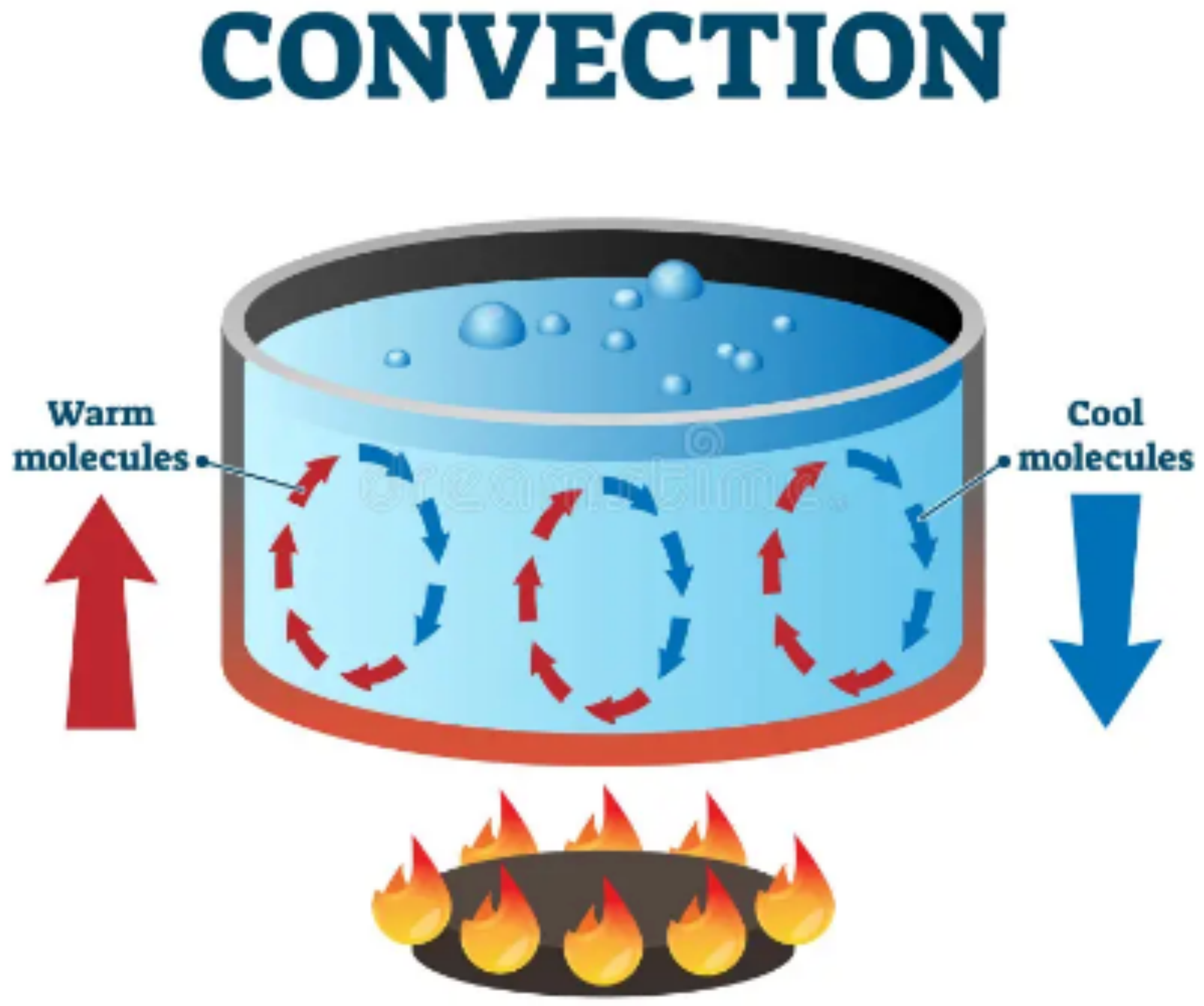
Keep it going…

Suppose, for the previous problem, that the materials are gold and iron (where $k_{\text{gold}} = 5\,k_{\text{iron}}$). What is the temperature in the middle?

Heat Transfer Mechanism #2: Convection

Heat by fluid currents. Difficult to describe quantitatively…





Heat Transfer Mechanism #3: Radiation

Heat by EM radiation. Power: $P_{\text{rad}} = e\sigma A T^4$

Clicker/Poll Question

One copper rod of dimensions L x w x h radiates at temperature T with net power P. Suppose you have a second copper rod of dimensions 2L x 2w x 2h. If the 2nd rod is also at temperature T, what is the net power radiated by the second rod?

A. P
B. 2P
C. 4P
D. 8P
E. 16P

Calorimetry: Gases

Because gases are relatively compressible, they can do work, and so the relationship between Q and T is process-dependent.

- Even if you have the same initial and final points on a pV diagram, Q depends on the path (why?)

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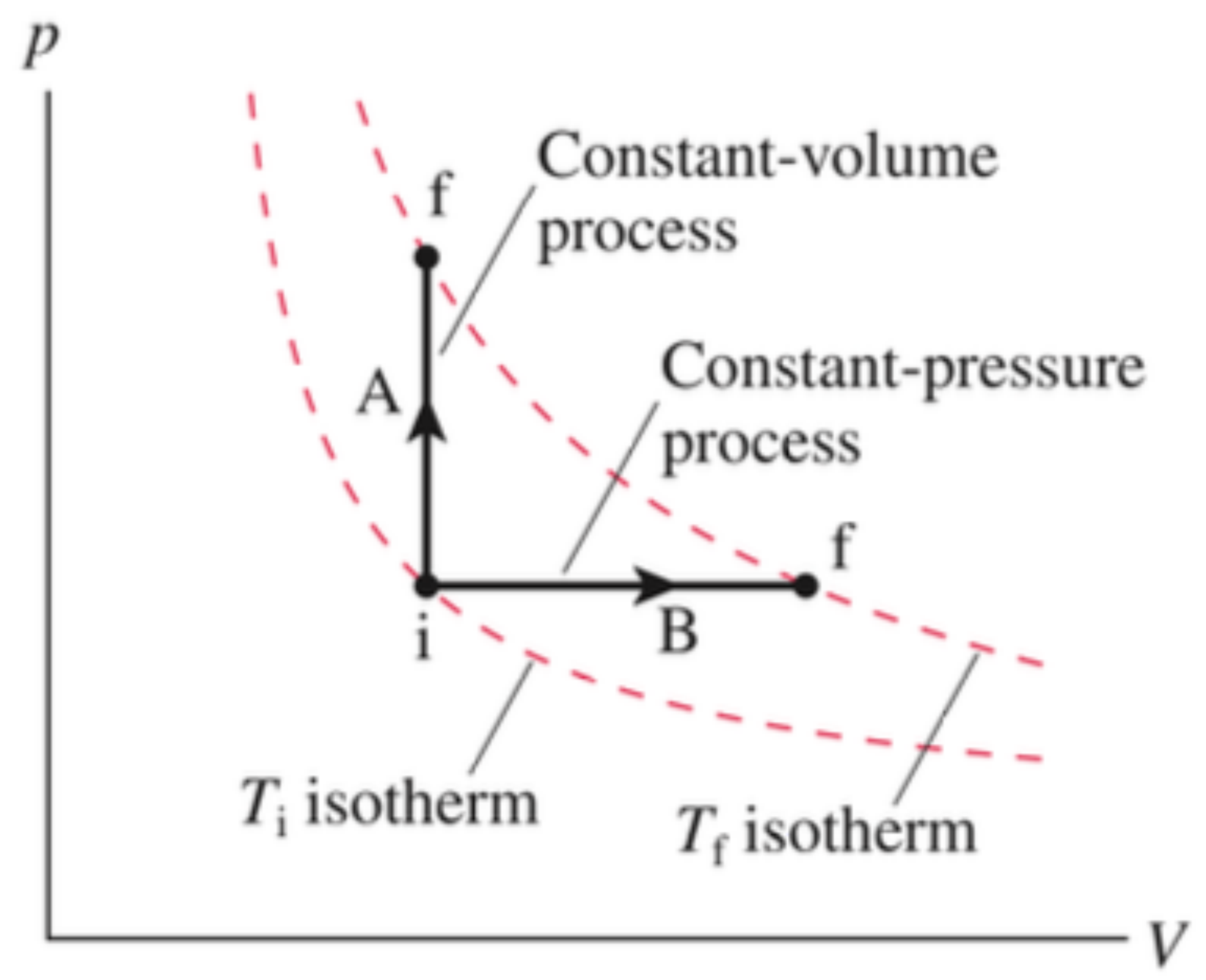
- Isobaric Heating: $Q = nC_p \Delta T$
- Isochoric Heating: $Q = nC_v \Delta T$
- Isothermal Heating: $Q \neq 0$, but $\Delta T = 0$ (!!!)

Clicker/Poll Question

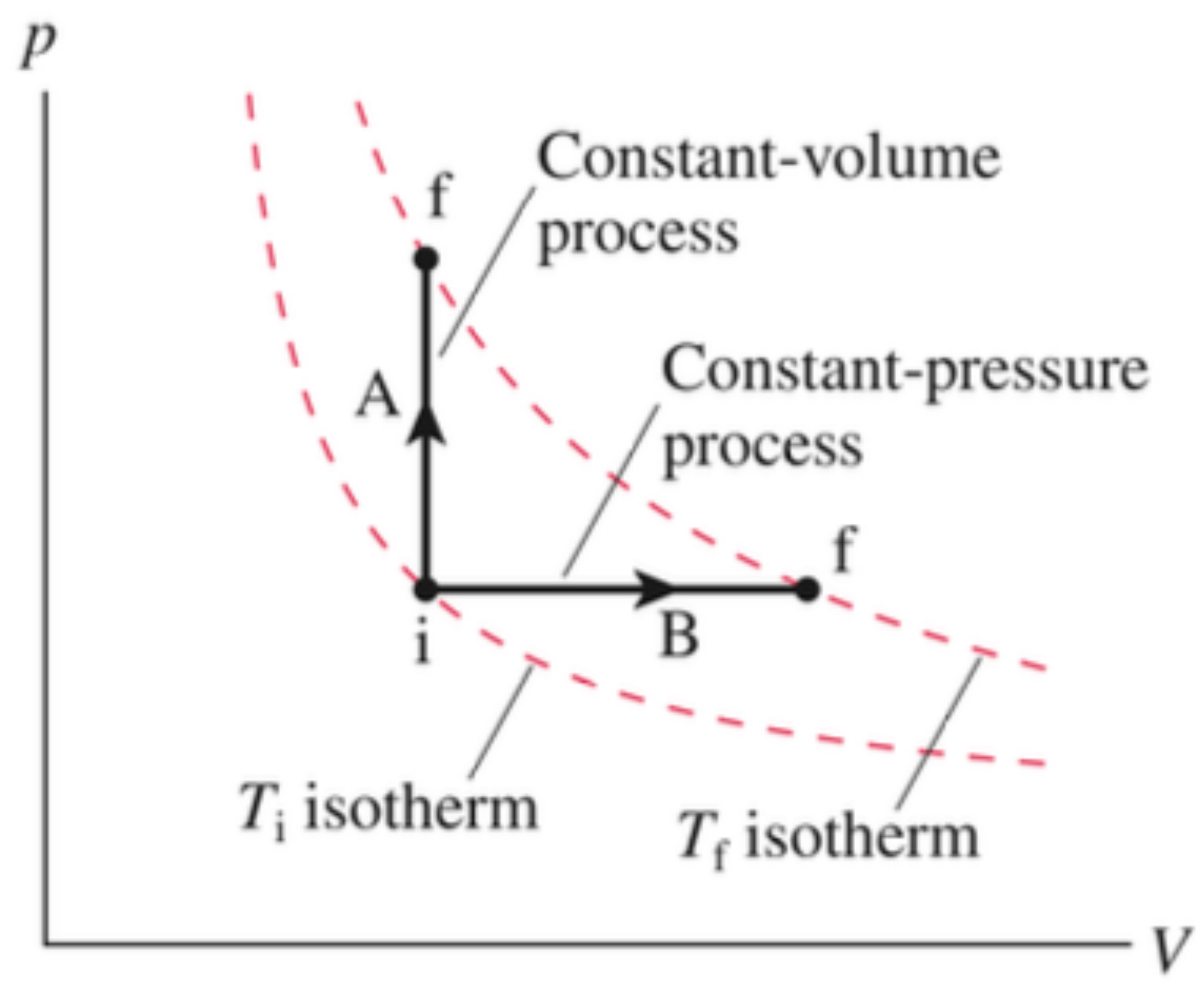
Two copies of the same amount of the same gas (A and B, w/ same number of moles) undergo processes A and B below. Which gas had more “heat delivered” to it? (remember, sloppy language!)

A. Gas A
B. Gas B
C. Same
D. I dunno



Relationship between C_p and C_v, Ideal Gases

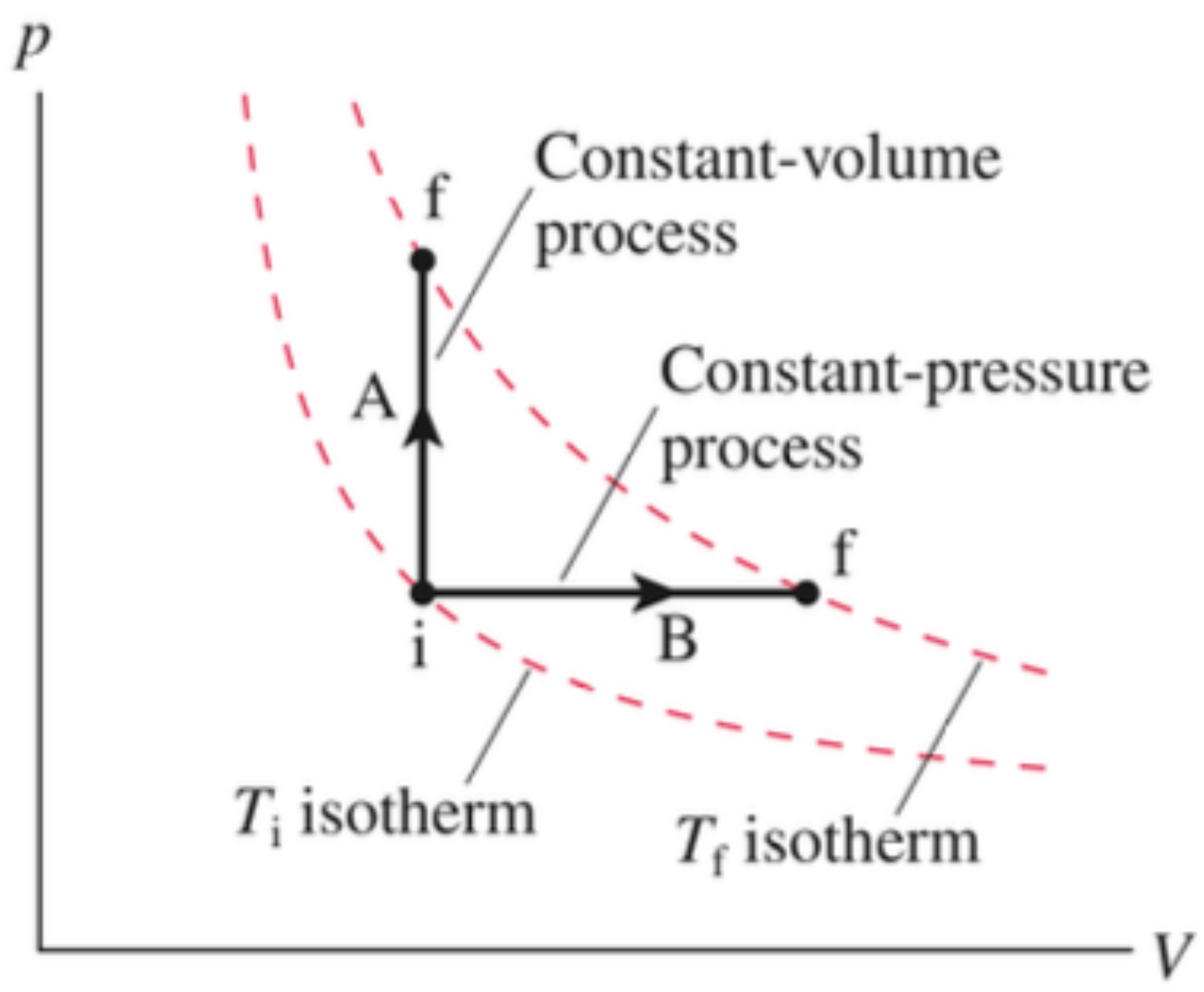
In the previous problem, you saw gas B had more heat delivered. $Q_B - Q_A > 0$ equals the area under line B, W_{by} (why?). Find two formulae for this work to show $C_p = C_V + R$.



Keep it going…

Suppose that 100J in the form of heat was added to gas A in order to go from i to f along the isochoric process. Take $C_v = (5/2)\,R$.

a) What is the heat added to gas B to get from i to f?
b) How much work was done by gas B?



Adiabatic Processes

A fourth path on pV-diagrams: those for which $Q = 0$ (no heat exchange).

Adiabats satisfy $pV^{\gamma} =$ constant, where $\gamma = \dfrac{C_p}{C_v}$ is the adiabatic constant.

$C_p > C_V$, which gives $\gamma > 1$, and so adiabats are "steeper than isotherms"

Clicker/Poll Question

A weather balloon is filled with helium and released. What kind of a process is approximated as the balloon rises in the air? Assume the balloon material is an excellent insulator.

A. Isobaric
B. Isochoric
C. Isothermal
D. Adiabatic

Clicker/Poll Question

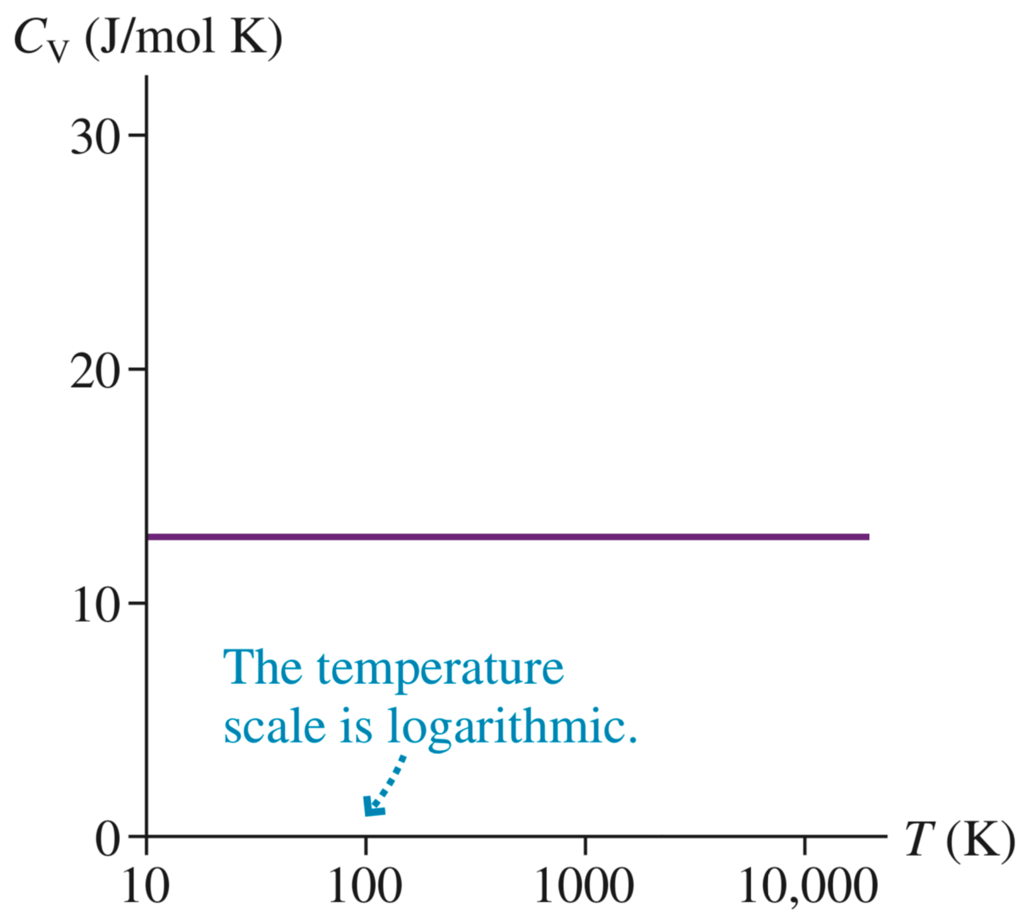
The pressure decreases as the balloon rises. What happens to the temperature of the Helium gas?

A. T increases
B. T decreases
C. T remains the same

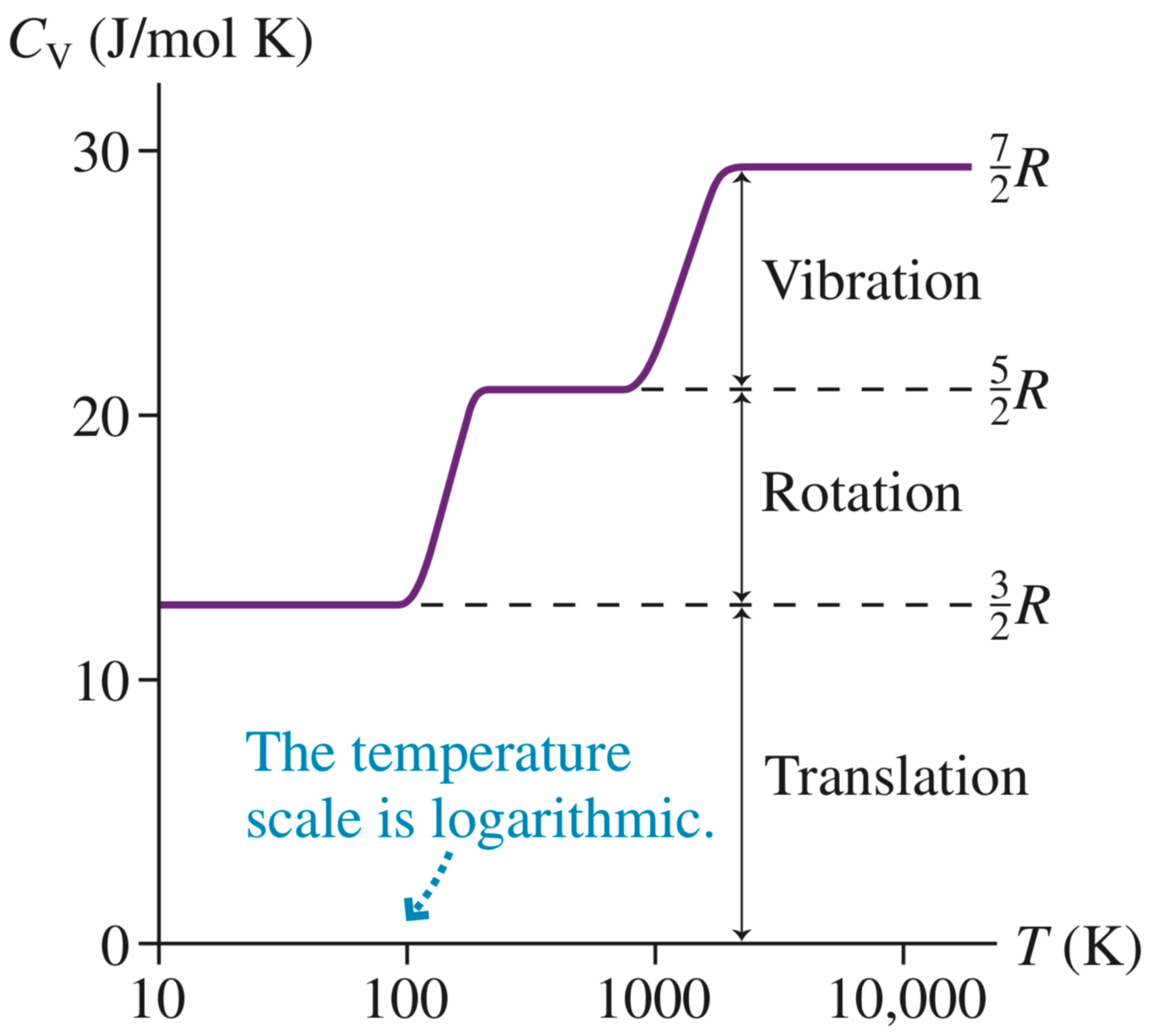
C_V as a function of temperature

$C_V = (5/3)R$ is constant for a monoatomic gas but increases with temperature for a diatomic gas. Why?

Monoatomic:
$C_V = (3/2)R$



Diatomic: $C_V \approx (5/2)$ *at room temp*



Answer: the diatomic gas has more “degrees of freedom” activated at higher temperatures.

Clicker/Poll Question

Suppose I have 10 J of energy that I want to give to a sample of air via heat. In order to get the largest temperature change, should I give this heat to the gas at 50 K or at 300 K ?

A. 50K
B. 300K
C. No difference

Equipartition Theorem

Each gas molecule stores (1/2)kT of energy for each degree of freedom (DoF, "f") accessible to the gas.

- Every gas molecule has 3 translational degrees of freedom available to it (moving in 3 dimensions).
    - Since a monoatomic gas can't rotate/vibrate, it always has exactly $f = 3$ DoF.
- Diatomic Molecules can have more…
    - At medium (room temp) and high temperatures: 2 more rotational DoF if it's a linear molecule; 3 if bent.
    - At high temperatures ($\gtrsim$1000K), 2 more "vibrational" DoF.

Some main formula

Equipartition Theorem: $\frac{1}{2}KT$ per DoF, per molecule

$$E_{\text{th}} = \frac{f}{2}kT \text{ per molecule}$$

$$K_{\text{trans}} = \frac{3}{2}kT = \frac{1}{2}mv_{\text{rms}}^2 \implies v_{\text{rms}} = \sqrt{\frac{3kT}{m}}$$

Clicker/Poll Question

For a monoatomic gas, what fraction of its total internal energy is translational kinetic?

A. 33.3%
B. 50.0%
C. 66.7%
D. 100%
E. Depends on the temperature.

Example

I add 75J of heat at constant pressure to 1mol of gas, and the temperature goes up by exactly 2.00 Kelvin.

a) What is the value of C_P? How many DoF does the gas have?
b) How much work was done by the gas in this process?

Example (continued)

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a) What is the value of C_P? How many DoF does the gas have?
b) How much work was done by the gas in this process?

Try it yourself…

Suppose that, in an isobaric expansion of a monoatomic gas, the gas does 1200 J of work on its surroundings. How much energy in the form of heat entered the gas during the expansion?

Agenda Today (May 1, 2025)

- Introduction to engines and refrigerators
- Engines
  - Energy Transfer Diagram
  - Definition of (Thermal) Efficiency of Engines
  - How to calculate given a pV diagram
  - Maximum efficiency / Carnot Engines
    - 2nd Law of Thermodynamics!
- Repeat the above, but for Refrigerators ("Fridges")

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Some Definitions; Engines and Refrigerators

- A closed path on a pV-diagram is called a “cycle”.
    - An ENGINE is a clockwise cycle… overall, heat is added to a gas, and the gas does work on its surroundings.
    - A REFRIGERATOR is a counterclockwise cycle… overall, work is done on the system, and heat is taken out of the system.

Example

Suppose you have an engine consisting of 4 steps:

1. isobaric expansion
2. adiabatic expansion
3. isobaric compression
4. isochoric heating

Draw this process on a pV diagram

Clicker/Poll Question

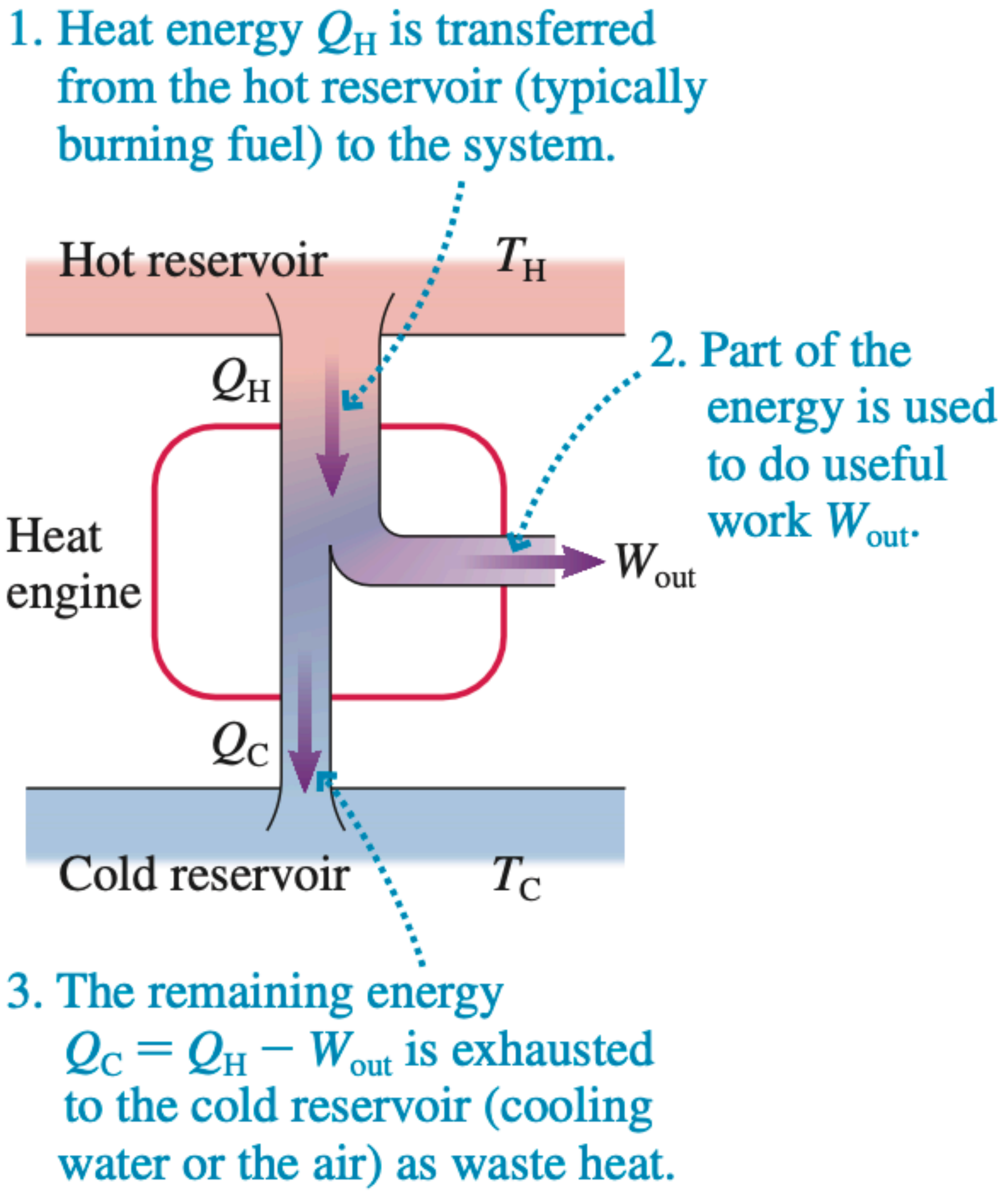
For the engine on the previous slide, under which step(s) is/are heat added to the gas?

A. Step 1 only
B. Step 3 only
C. Step 4 only
D. Steps 1 and 4 only
E. Steps 3 and 4 only

Engine Efficiency

An engine takes in heat, outputting work and "waste heat." $Q_H = W_{\text{out}} + Q_C$.

FIGURE 21.5 The energy-transfer diagram of a heat engine.



Clicker/Poll Question

An engine has an efficiency equal to 0.20. This means that, for every 1.0kJ of “waste heat” that I produce, that I have gotten _____ of work.

A. 2.0 kJ
B. 5.0 kJ
C. 0.20 kJ
D. 0.25 kJ
E. None of these

Calculating Engine Efficiency, η

For each step on a pV diagram, determine if Q is pos or neg.

- Add |Q| for all negative Qs: this is the total waste heat, Q_C
- Add Q for all positive Qs: this is the heat input, Q_H
- Find the net work done by the system (the area inside the closed path: this is the work output, W_{out}

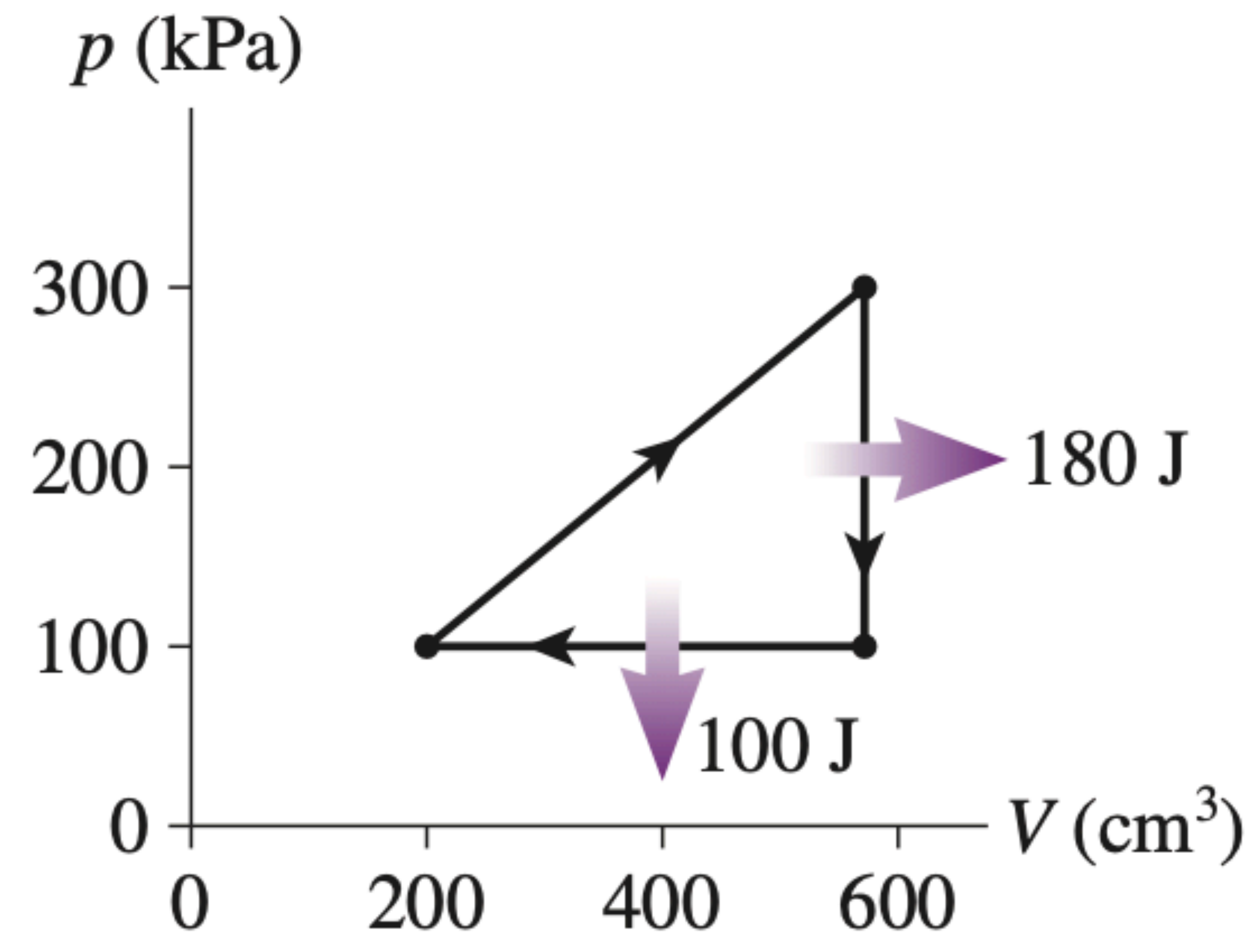
$$\boxed{\eta = \frac{W_{\text{out}}}{Q_{\text{H}}} = \frac{\text{what you get}}{\text{what you had to pay}}}$$

Also, since $W_{\text{out}} = Q_H - Q_C$,

we can write this as $\eta = 1 - \dfrac{Q_C}{Q_H}$

Example

Find the engine efficiency for the given pV diagram. Heats leaving the gas are shown.



Maximum Engine Efficiency / 2nd Law of Thermo

There are various ways of saying the 2nd law of thermodynamics. One is called the "Kelvin statement," which says:

1. There are no perfect engines ($Q_C > 0$).
2. For all engines operating between temperatures T_C and T_H, no engine has efficiency better than the Carnot efficiency:

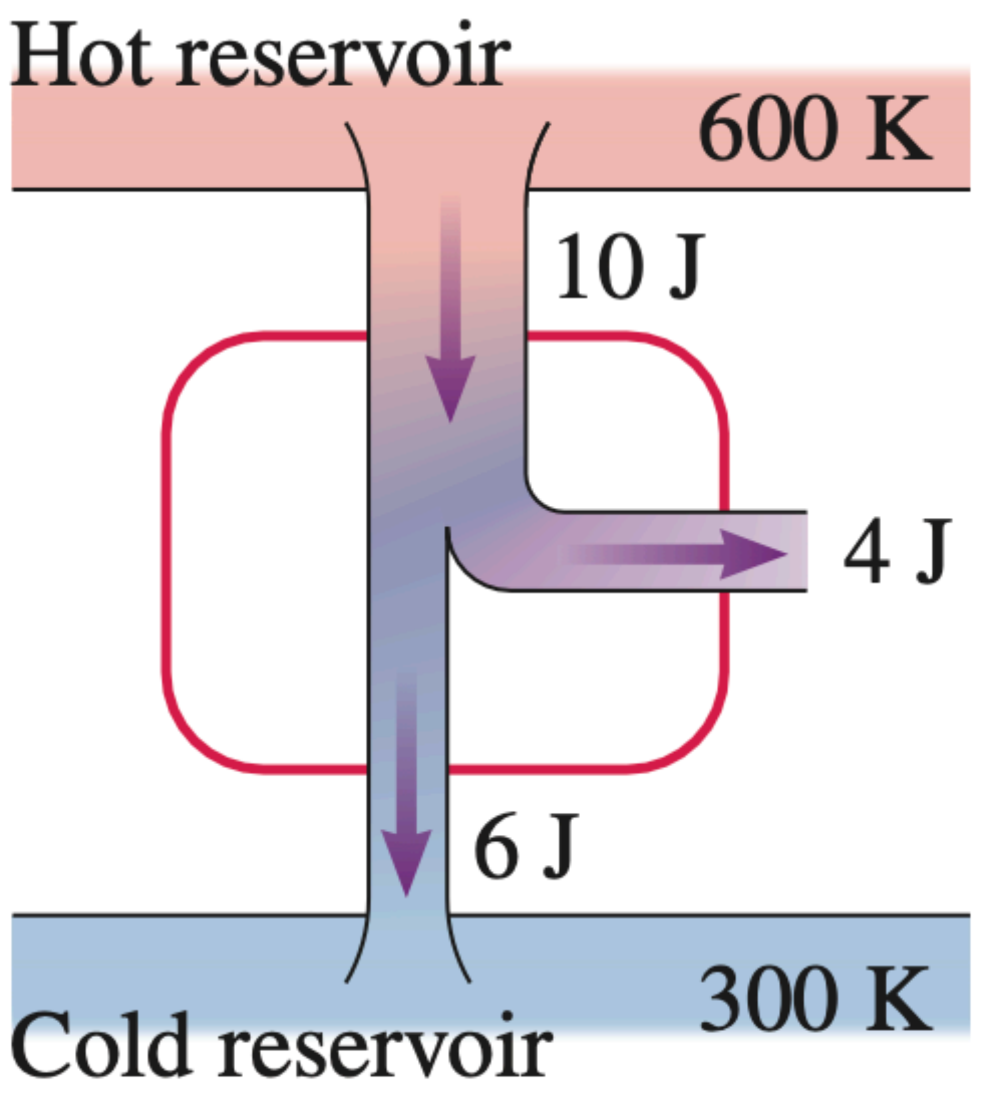
$$\eta \leq \eta_{\text{max}} = \eta_{\text{Carnot}} = 1 - \frac{T_C}{T_H}$$

(The Carnot engine consists of 2 isotherms and 2 adiabats)

Clicker/Poll Question

Is this energy-transfer diagram a possible engine?

A. Yes
B. No
C. Not enough info



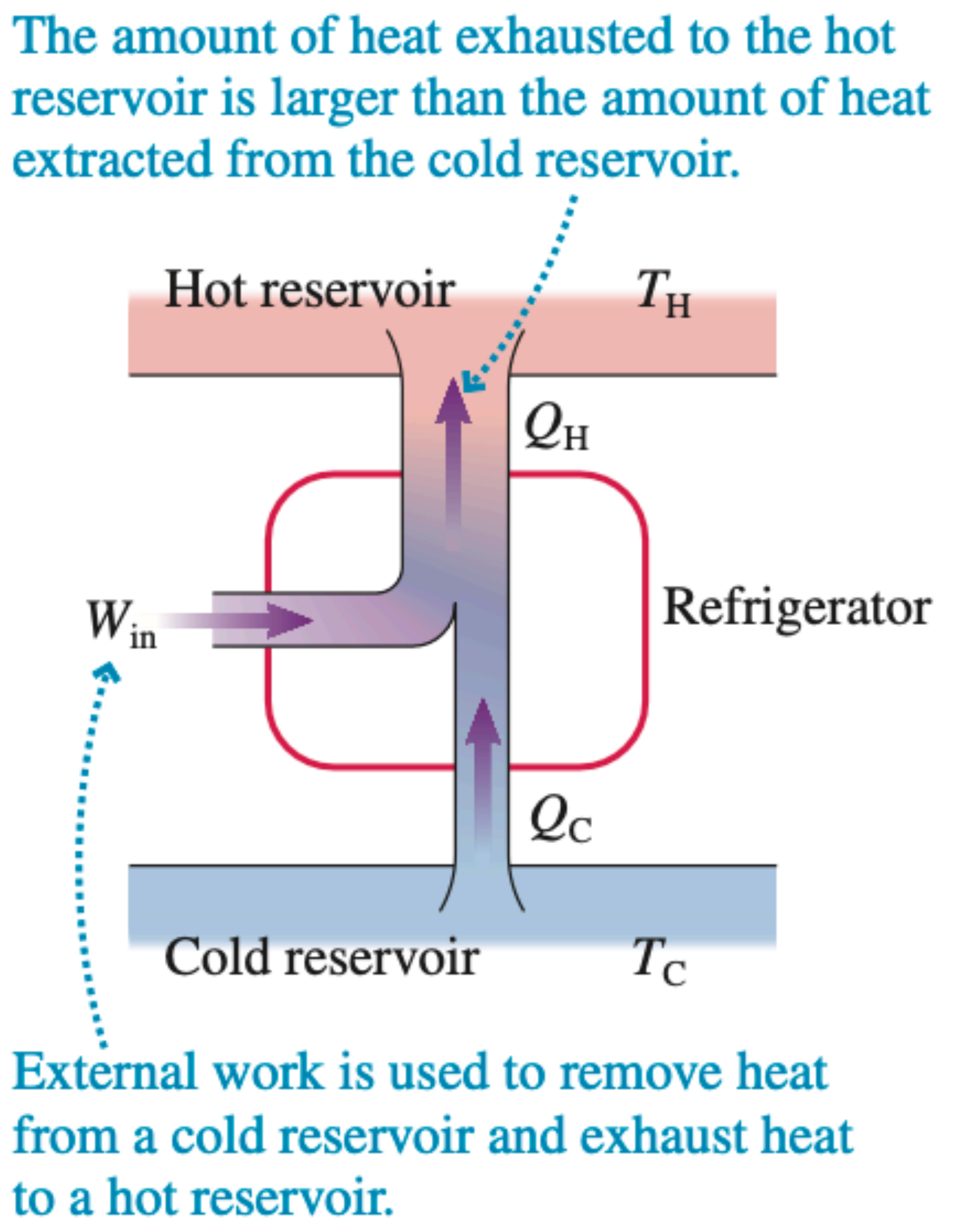
Refrigerators and “Coefficient of Performance” K

A fridge takes in heat and input work, and expels the heat at a higher-temperature reservoir. $Q_H = W_{\text{in}} + Q_C$.

$$\boxed{K = \frac{Q_C}{W_{\text{in}}} = \frac{\text{what you get}}{\text{what you had to pay}}}$$

Also, since $W_{\text{in}} = Q_H - Q_C$, we can write this as $K = \dfrac{Q_C}{Q_H - Q_C}$

FIGURE 21.10 The energy-transfer diagram of a refrigerator.



Maximum Fridge Efficiency / 2nd Law of Thermo

There are various ways of saying the 2nd law of thermodynamics. One is called the “Clausius statement,” which says:

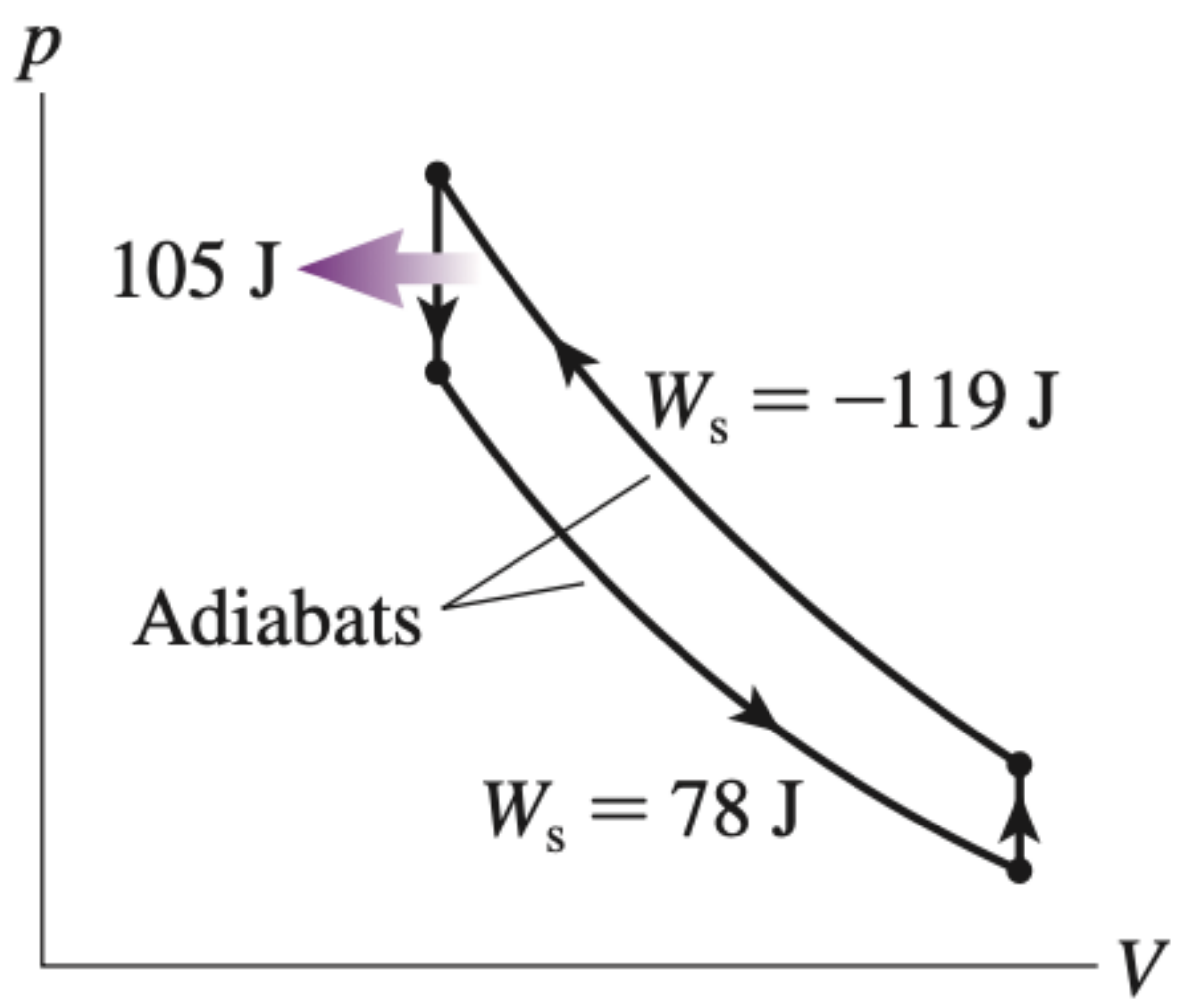
1. There are no perfect refrigerators ($W_{\text{in}} > 0$).
2. For all refrigerators operating between temperatures T_C and T_H, no fridge has COP better than the Carnot COP:

$$K \leq K_{\text{max}} = K_{\text{Carnot}} = \frac{T_C}{T_H - T_C}$$

(The Carnot engine consists of 2 isotherms and 2 adiabats)

Example

What are (a) the heat extracted from the cold reservoir and (b) the coefficient of performance for the refrigerator shown in the figure?



Try it yourself…

A heat engine using 120mg of helium as the working substance follows the cycle shown in the figure.

a. Determine the pressure, temperature, and volume of the gas at points 1, 2, and 3.
b. What is the engine's thermal efficiency?
c. What is the maximum possible efficiency of a heat engine that operates between T_{max} and T_{min}?