Applying Physics Education Research to Teaching Thermodynamics

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Collaborators

- Tom Greenbowe (Iowa State University Chemistry)
- John Thompson (U. Maine Physics)

Students

- Ngoc-Loan Nguyen (M.S. 2003)
- Warren Christensen (Ph.D. student)
- Tom Stroman (new grad student)

Funding

- NSF Division of Undergraduate Education
- NSF Division of Physics

Student Learning of Thermodynamics

- There have been more than 200 investigations of pre-college students' learning of thermodynamics concepts.
- Recently published study of university students showed substantial difficulty with work concept and with the first law of thermodynamics. *M.E. Loverude, C.H. Kautz, and P.R.L. Heron, Am. J. Phys.* ***70****, 137 (2002).*
- Until recently there has been only limited study of thermodynamics knowledge of students in introductory (first-year) calculus-based general physics course.

Common Difficulties at Pre-College Level

- Inability to distinguish "heat" [*magnitude of energy transfer due to temperature difference*] and "temperature" [*average kinetic energy per molecule*]
- Confusion between thermal conductivity and temperature (e.g., highly conductive materials seem "cold" to the touch)
- Problems with multivariable equations such as Ideal Gas Law $PV=nRT$
  - *tendency to ignore possible variation of one or more variables when solving problems*

Physics Students' Reasoning in Calorimetry

N.-L. Nguyen, W. Christensen, and DEM

- Investigation of reasoning regarding calorimetric concepts among students in calculus-based general physics course
- Development and testing of curricular materials based on research

Investigation of student learning in calculus-based physics course (PHYS 222 at Iowa State)

Question #1

*Written test given **after** lecture instruction completed*

The specific heat of water is ***greater*** than that of copper.

A piece of copper metal is put into an insulated calorimeter which is nearly filled with water. The mass of the copper is the ***same*** as the mass of the water, but the initial temperature of the copper is *lower* than the initial temperature of the water. The calorimeter is left alone for several hours.

During the time it takes for the system to reach equilibrium, will the temperature change (number of degrees Celsius) of the copper be *more than, less than,* or *equal to* the temperature change of the water? Please explain your answer.

Answer: **The temperature change for copper is larger.**

Question #1 Solution

$$Q = mc\Delta T$$

$$|Q_{Cu}| = |Q_W| \quad \text{and} \quad m_{Cu} = m_W$$

$$\Rightarrow c_{Cu}\Delta T_{Cu} = c_W \Delta T_W$$

$$\Delta T_{Cu} = \frac{c_W}{c_{Cu}} \Delta T_W$$

$$c_W > c_{Cu} \Rightarrow \Delta T_{Cu} > \Delta T_W$$

Notation: ΔT ≡ absolute value *of temperature change*

Question #1 Results

Second-semester calculus-based course (PHYS 222)

	N=311
Correct	
$\Delta T_{LSH} > \Delta T_{GSH}$	62%
With correct explanation	***54%***
Incorrect	
$\Delta T_{LSH} = \Delta T_{GSH}$	**22%**
$\Delta T_{LSH} < \Delta T_{GSH}$	16%

LSH = lower specific heat
GSH = greater specific heat

(five different versions of question were administered)

Question #1 Explanations

N=311

Incorrect ($\Delta T_{LSH} = \Delta T_{GSH}$)	**22%**
Temperature changes are equal since energy transfers are equal	9%
Temperature changes are equal since system goes to equilibrium	6%
Other	6%

Example of Incorrect Student Explanation

"*Equal, to reach thermal equilibrium, the change in heat must be the same, heat can't be lost, they reach a sort of "middle ground" so copper decreases the same amount of temp that water increases*."

"Equal energy transfer" is assumed to imply "equal temperature change"

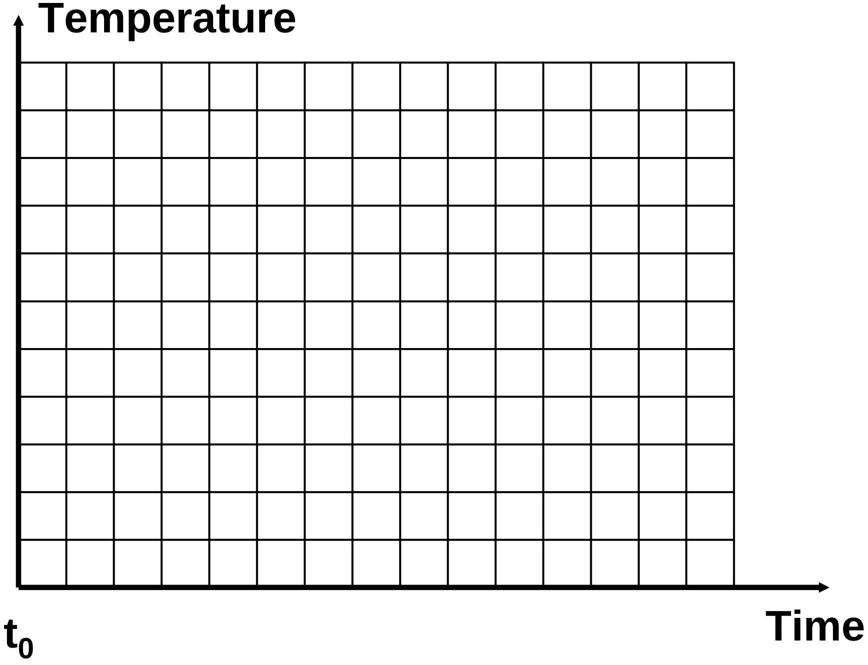
Question #2

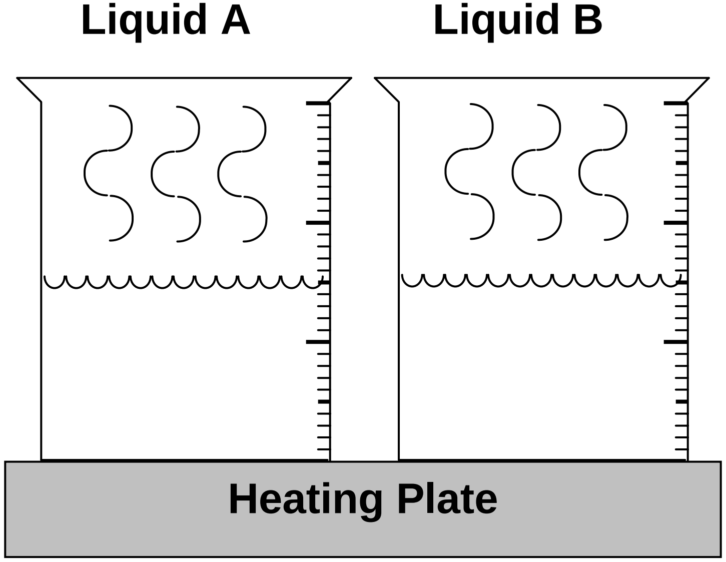
Suppose we have two ***separate*** containers: One container holds Liquid A, and another contains Liquid B. The mass and initial temperature of the two liquids are the same, but the ***specific heat*** of Liquid A is ***two times*** that of Liquid B.

Each container is placed on a heating plate that delivers the ***same rate of heating*** in joules per second to each liquid beginning at initial time $\mathbf{t_0}$.

Question #2 Graph

$[c_A = 2c_B]$





The specific heat of A is greater than the specific heat of B.

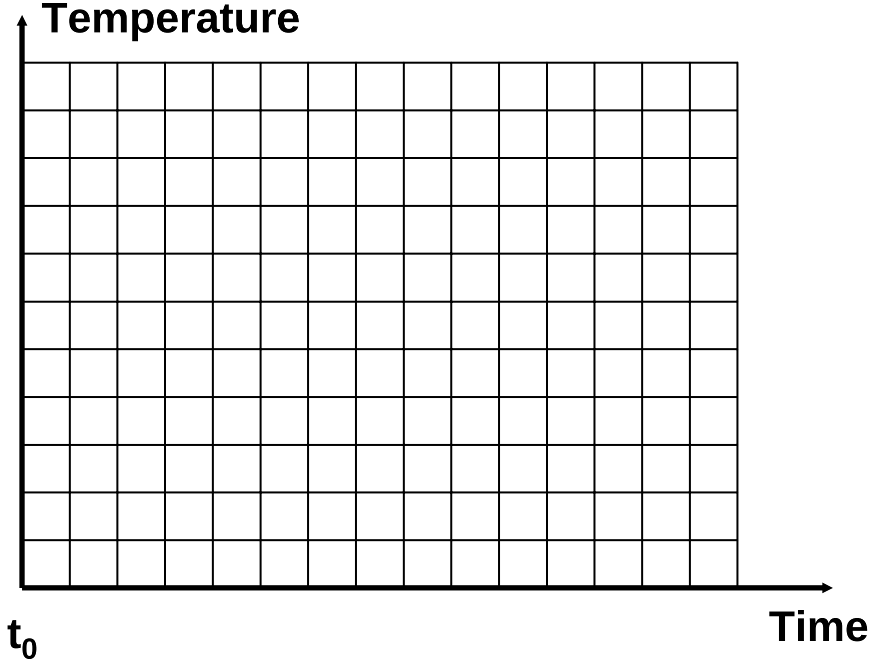
Question #2 (cont’d)

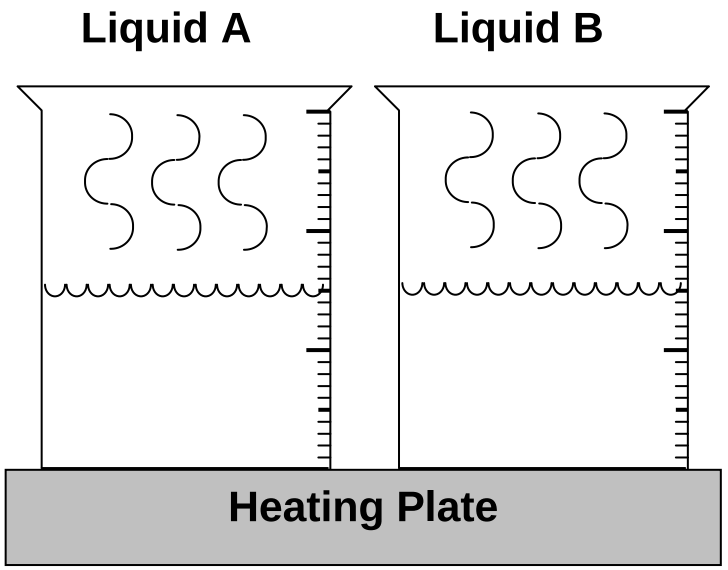
On the grid below, graph the temperature as a function of time for *each* liquid, A and B. Use a separate line for each liquid, even if they overlap. Make sure to clearly <u>label</u> your lines, and use proper graphing techniques.

Please **explain** the reasoning that you used in drawing your graph.

Question #2 Graph

$[c_A = 2c_B]$





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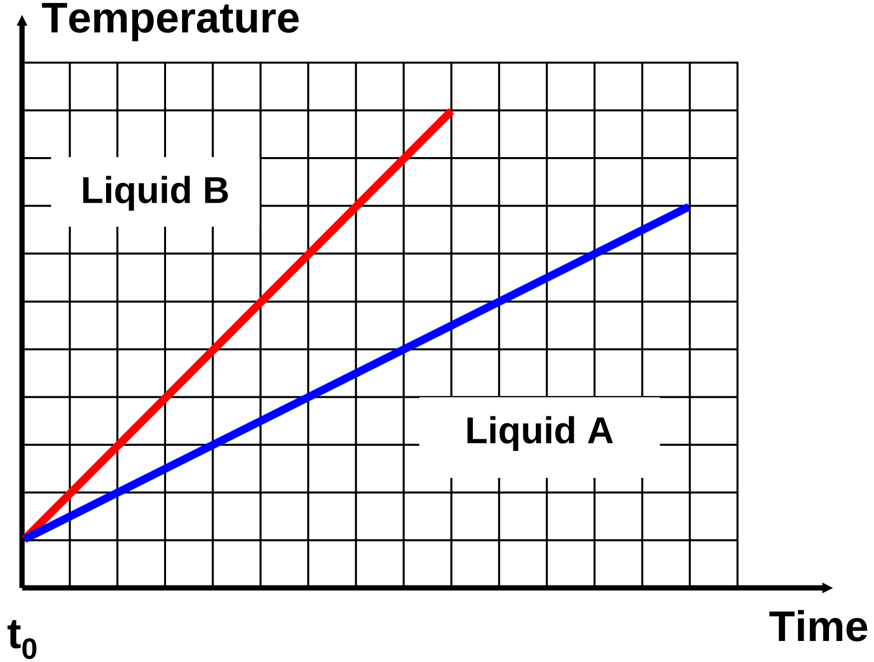
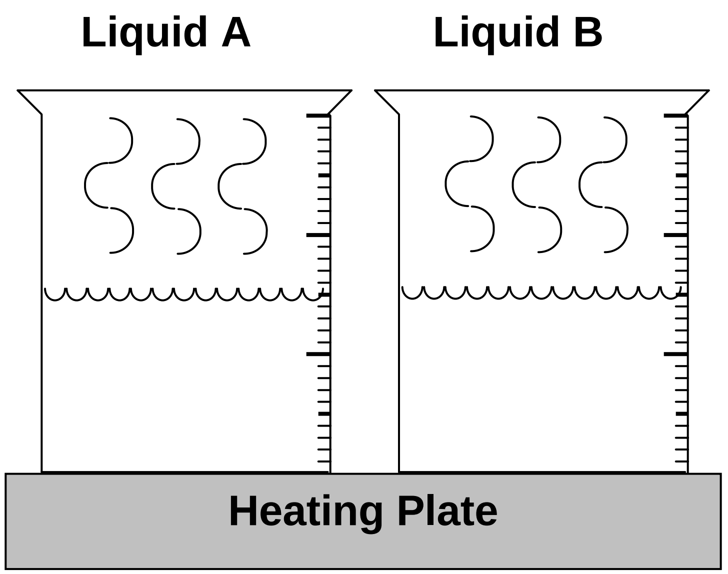




The specific heat of A is greater than the specific heat of B.

Question #2 Results (N = 311)

Second-semester calculus-based course (PHYS 222)

Correct *(Slope of B > A)*	70%
with correct explanation	50%
Incorrect	
Slope of B < A	28%
Other	2%

Example of Incorrect Student Explanation

"Since the specific heat of A is two times that of liquid B, and everything else is held constant … the liquid of solution A will heat up two times as fast as liquid B."

Belief that specific heat is proportional to rate of temperature change

Implementation of Instructional Model

"Elicit, Confront, Resolve" (U. Washington)

- Guide students through reasoning process in which they tend to encounter targeted conceptual difficulty
- Allow students to commit themselves to a response that reflects conceptual difficulty
- Guide students along alternative reasoning track that bears on same concept
- Direct students to compare responses and resolve any discrepancies

Implementation of Instructional Model

"Elicit, Confront, Resolve" (U. Washington)

One of the central tasks in curriculum reform is development of "Guided Inquiry" worksheets

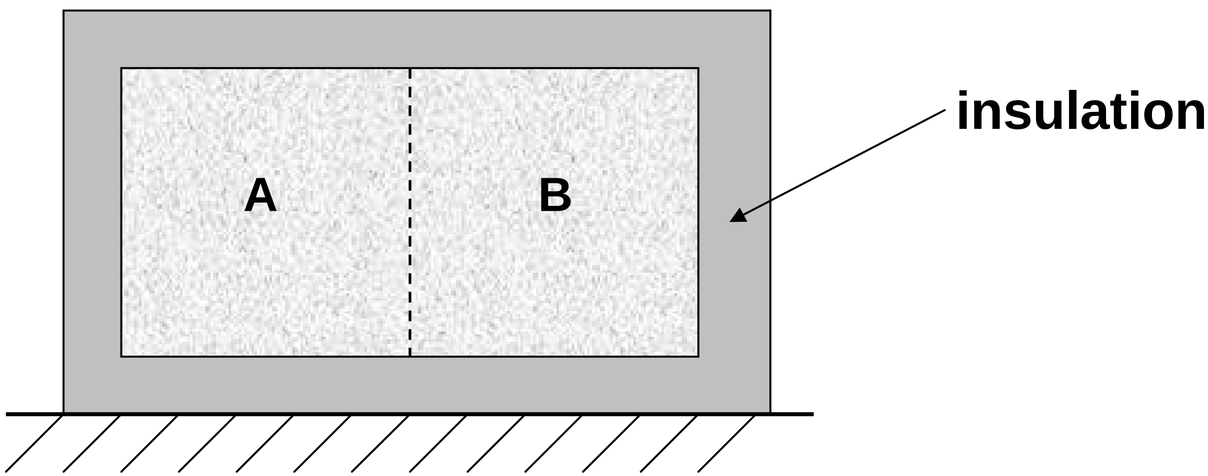
- Worksheets consist of sequences of closely linked problems and questions
  - *focus on conceptual difficulties identified through research*
  - *emphasis on qualitative reasoning*
- Worksheets designed for use by students working together in small groups (3-4 students each)
- Instructors provide guidance through "Socratic" questioning

Worksheet Strategy

- Guide students to confront distinction between temperature of a system, and its internal energy
- Explore meaning of specific heat by finding temperature changes of different objects in thermal contact with each other
- Practice proportional reasoning and algebraic skills by varying system parameters, gradually increasing problem complexity.

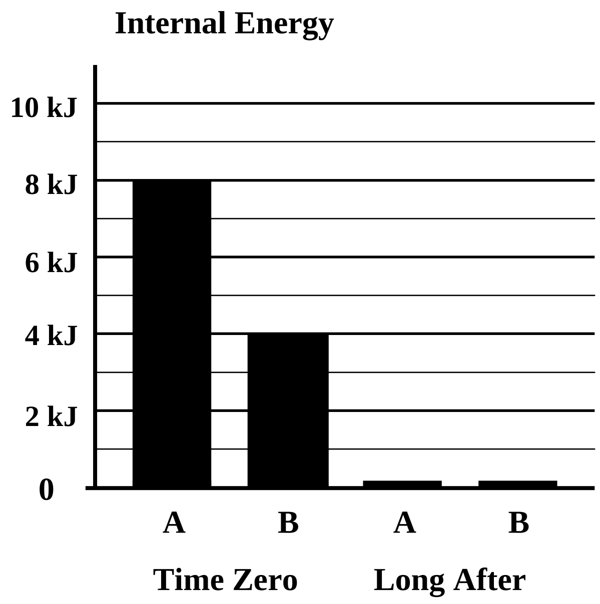
Ideal Gas Problem

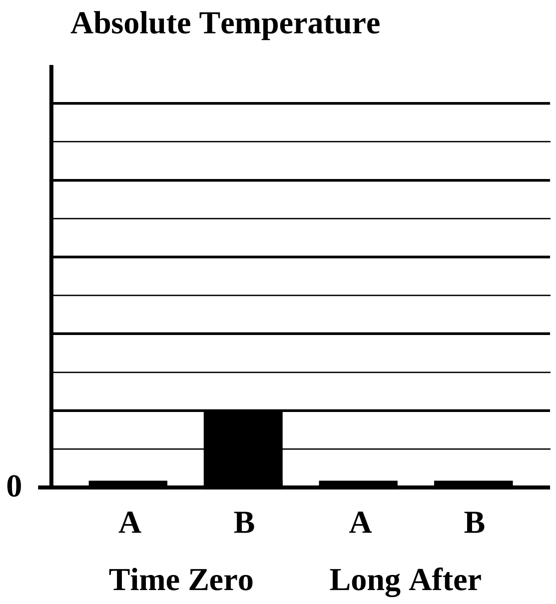
Suppose we have two samples, *A* and *B*, of an **ideal gas** placed in a partitioned insulated container which neither absorbs energy nor allows it to pass in or out.



Calorimetry Worksheet

Complete the bar charts by finding the “Long After” values for temperature and internal energy, and also the amounts of energy transferred to each sample.





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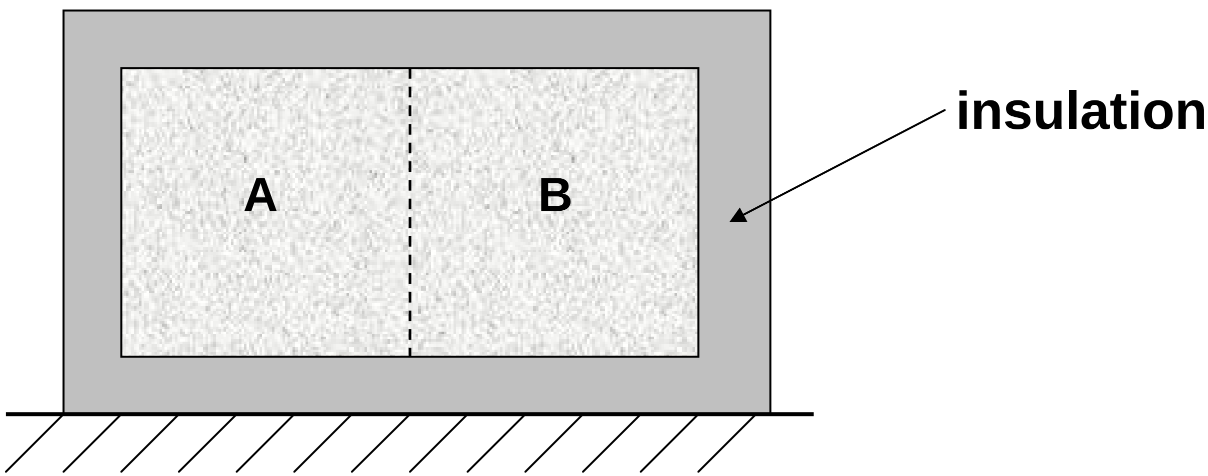
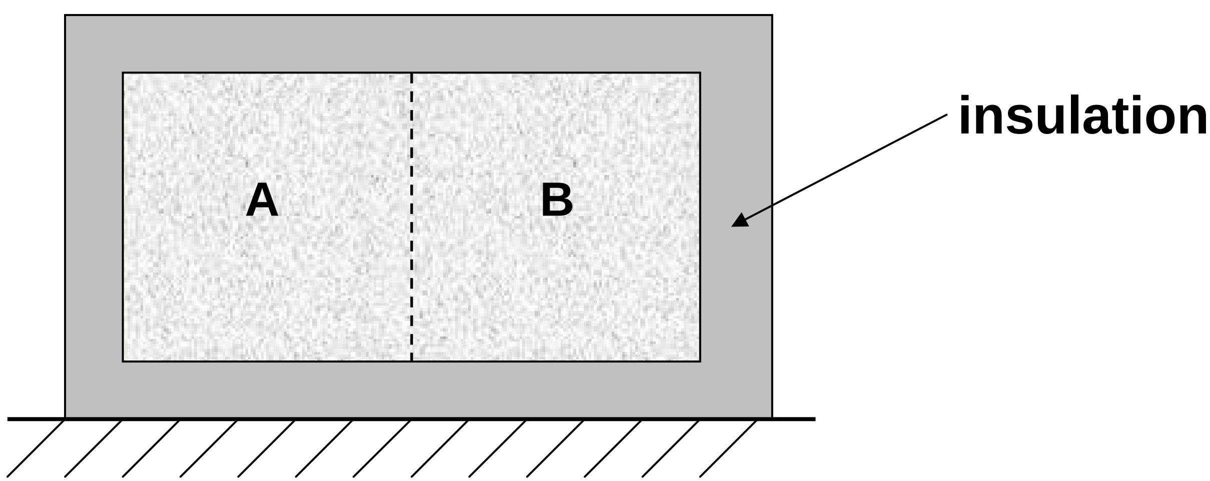
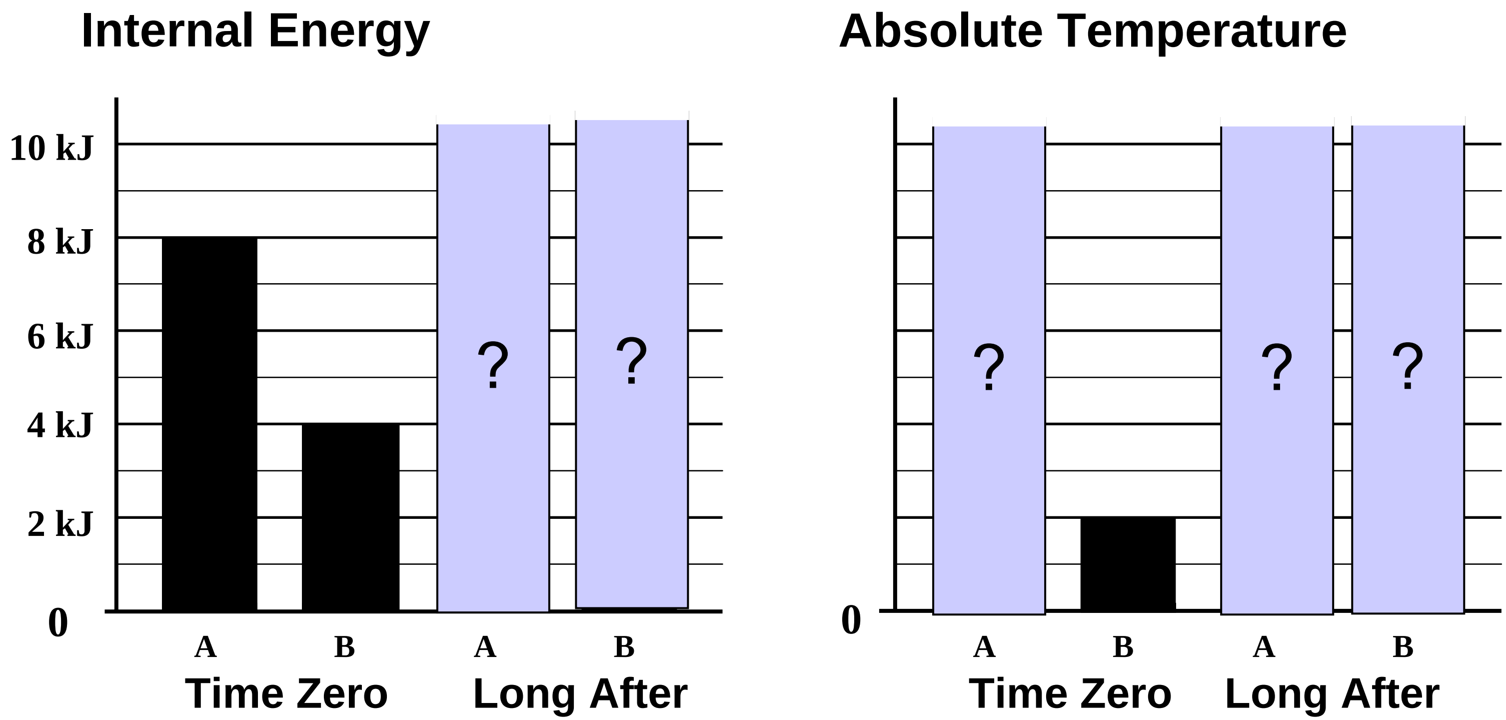


Ideal Gas Problem

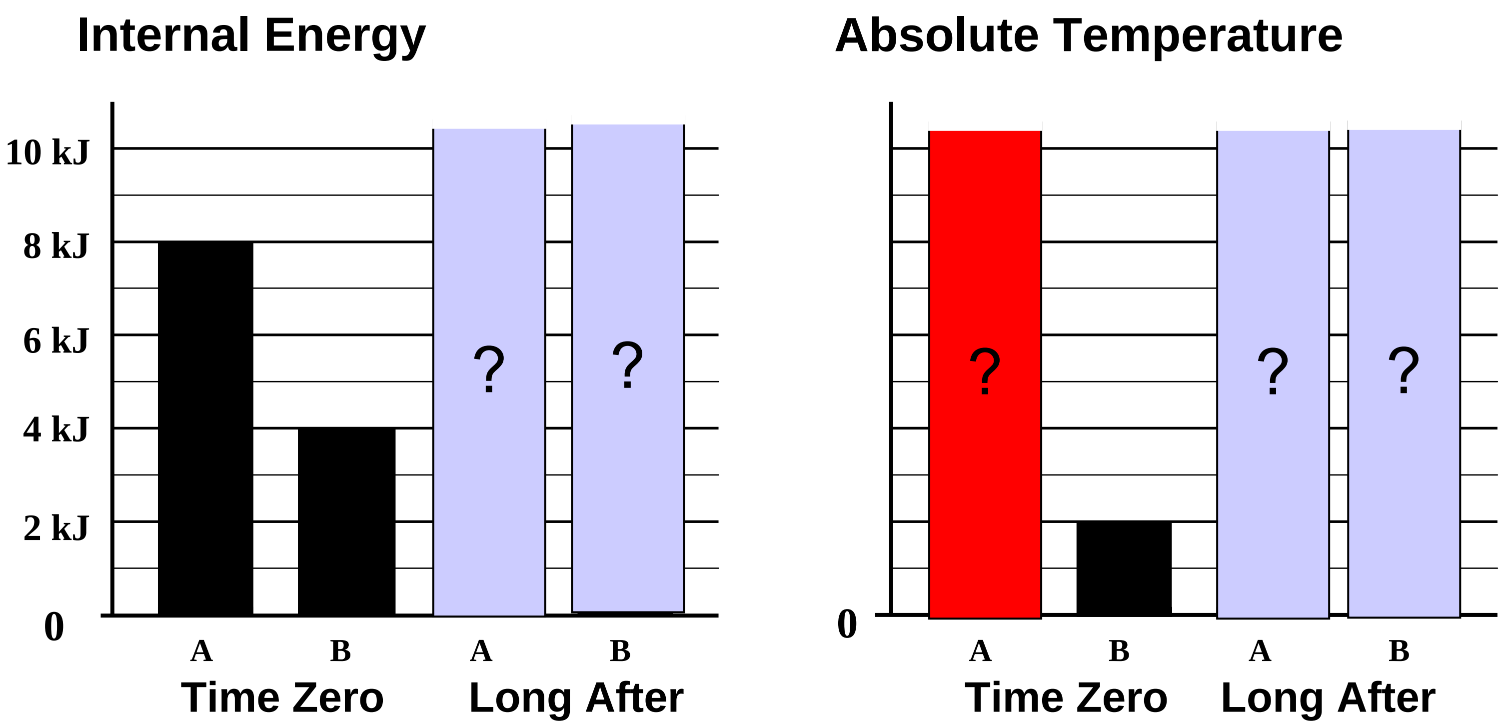
Suppose we have two samples, *A* and *B*, of an **ideal gas** placed in a partitioned insulated container which neither absorbs energy nor allows it to pass in or out. The gas in sample *A* is the **same gas** that is in Sample *B*. Sample *A* has the **same mass** as sample *B* and each side of the partition has the same volume**.** Energy but no material can pass through the conducting partition; the partition is rigid and cannot move.



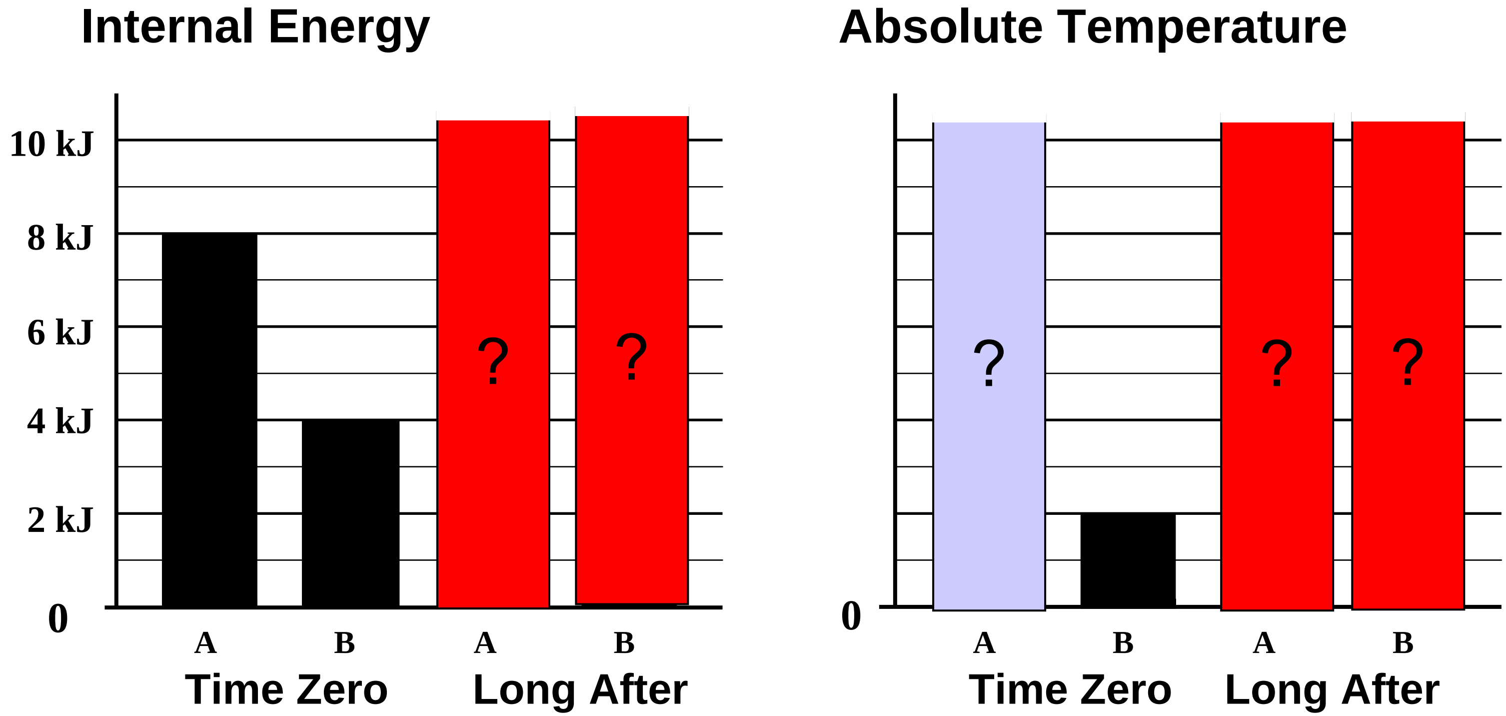
Given Information: Initial values of internal energy of A and B, and temperature of B



Find the absolute temperature of sample *A* at time zero (the initial time), and plot it on the chart.



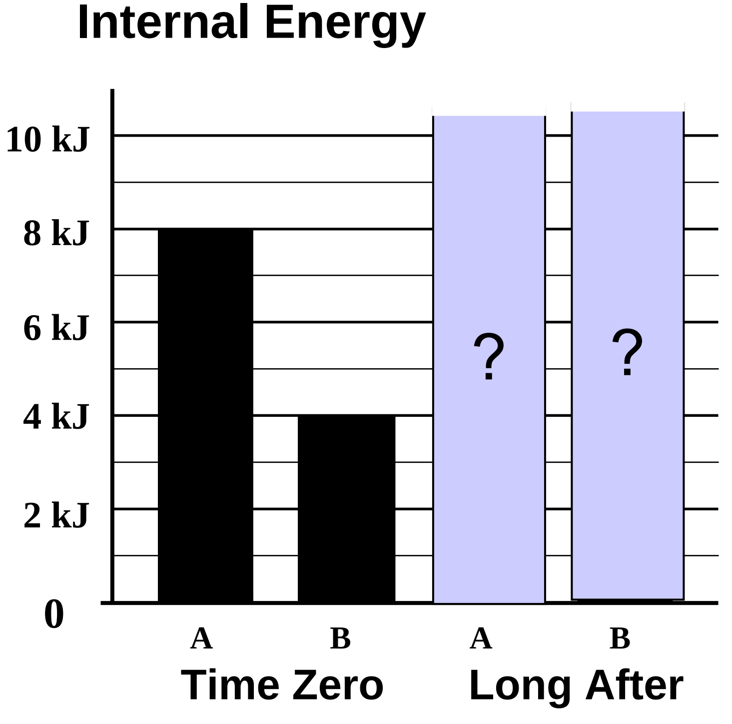
Find the absolute temperature of sample *A* at time zero (the initial time), and plot it on the chart. Complete the bar charts by finding the "Long After" values for temperature and internal energy. Explain your reasoning.

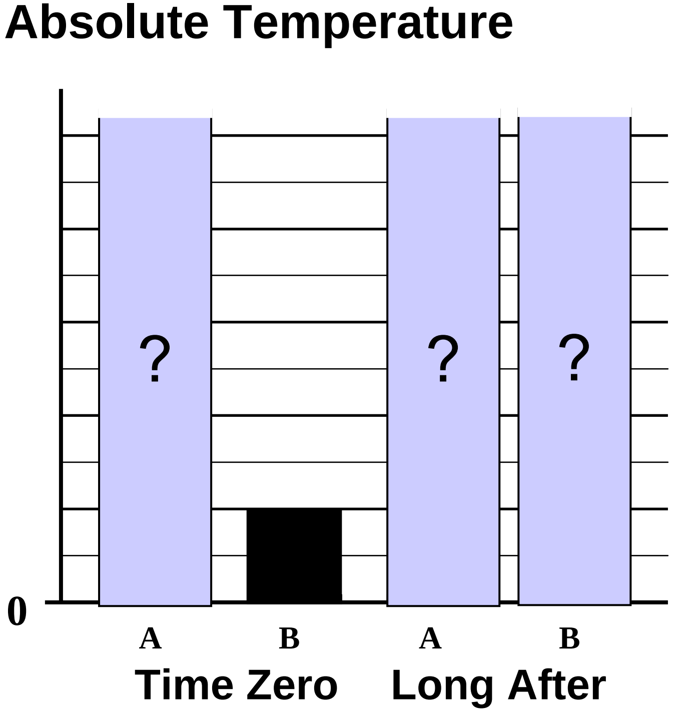


Ideal Gas Bar Graph Solution

with same mass

$$U = \frac{3}{2} NkT;$$



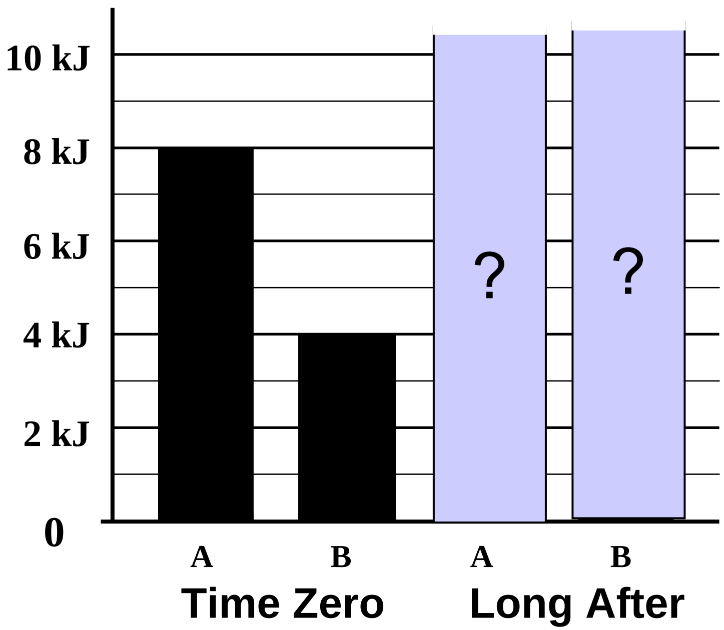


Ideal Gas Bar Graph Solution

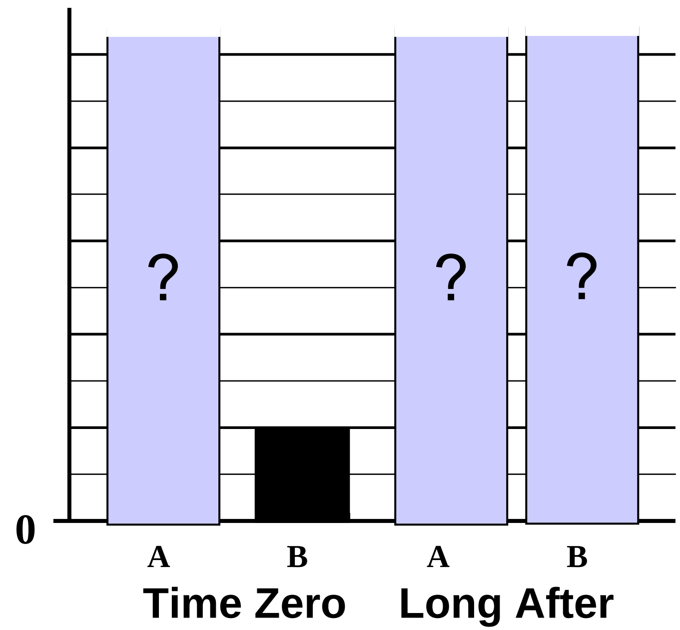
with same mass

$$U = \frac{3}{2} NkT; \qquad \text{Equal masses of ideal gas} \Rightarrow \qquad \frac{T_A}{T_B} = \frac{U_A}{U_B}$$

Internal Energy



Absolute Temperature



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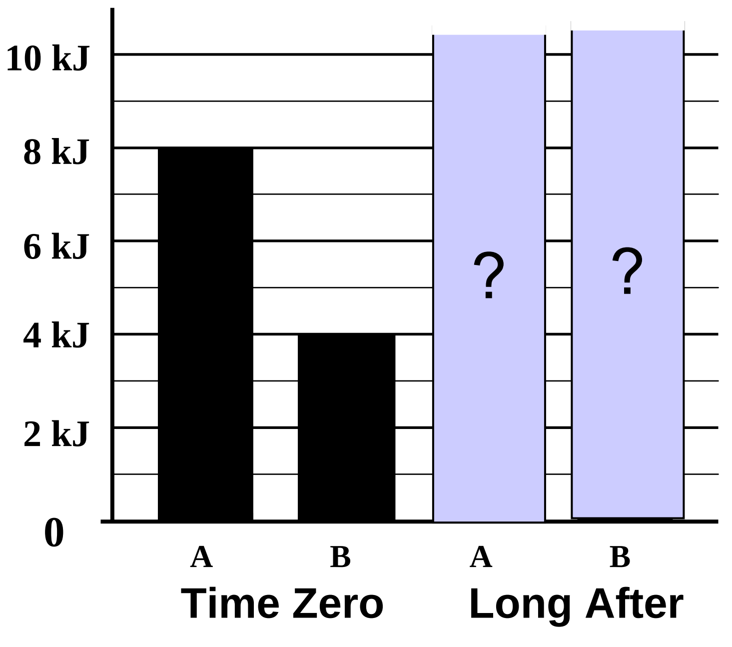

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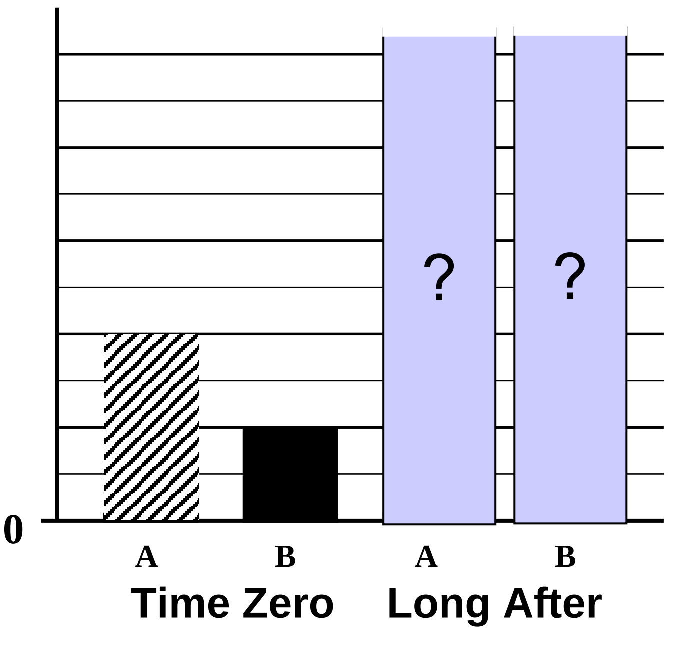

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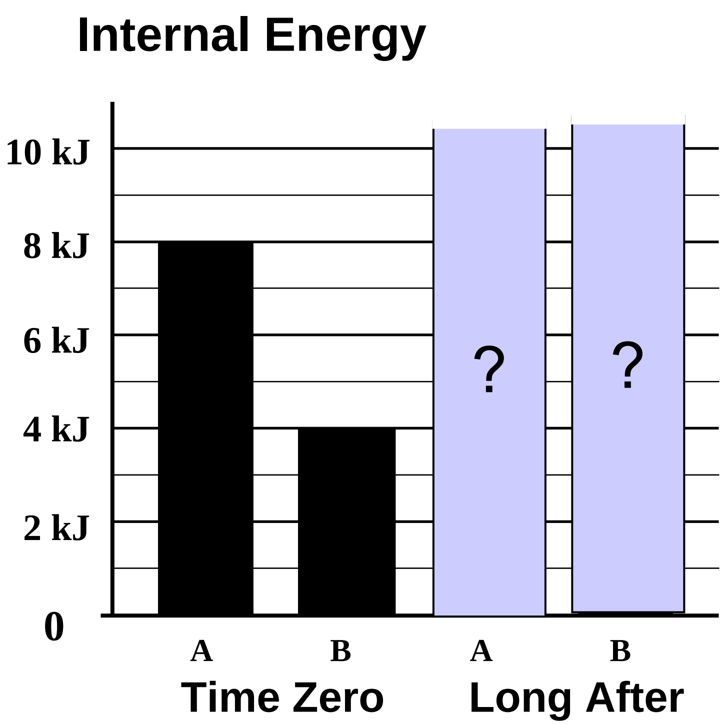
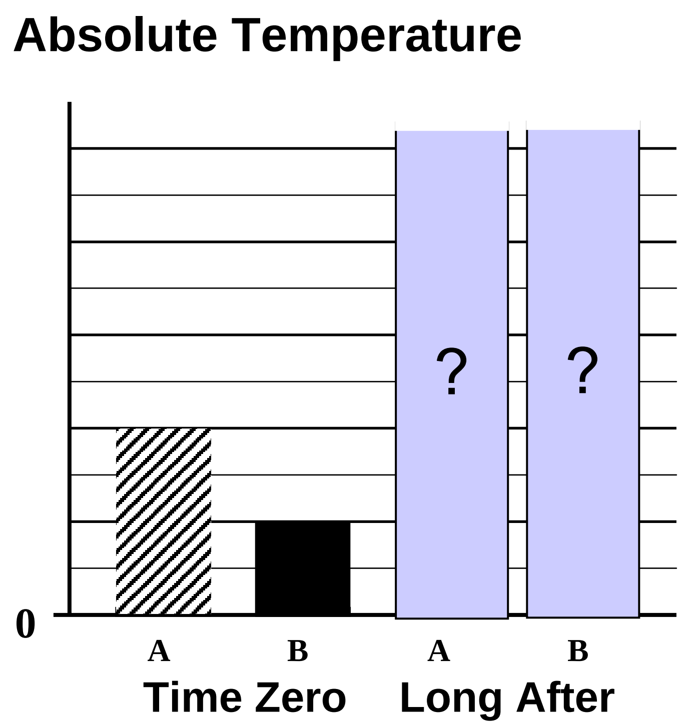
with same mass

energy lost by *A* = energy gained by *B*





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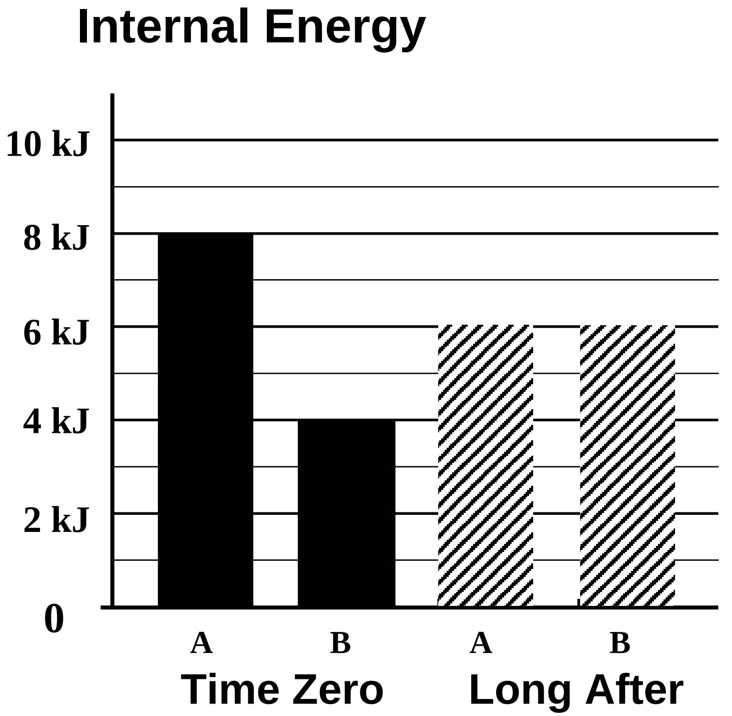
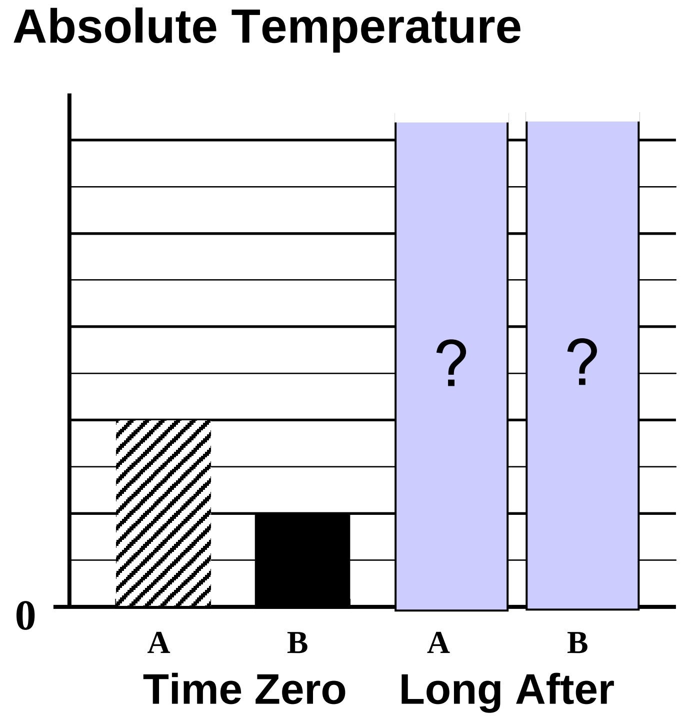
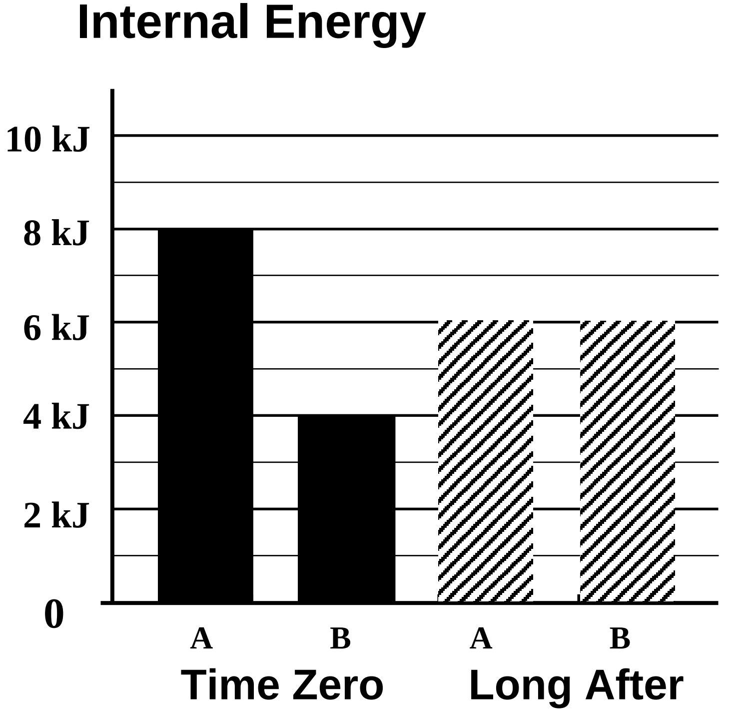


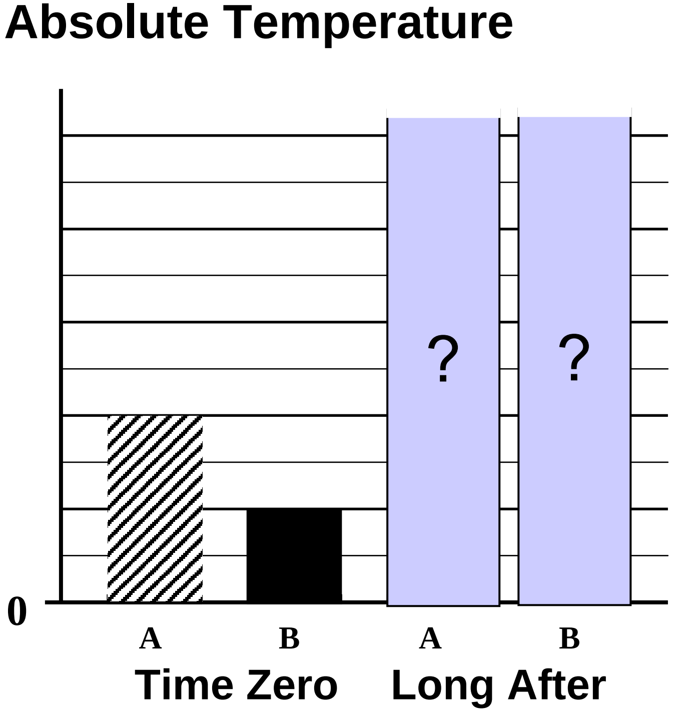


Ideal Gas Bar Graph Solution

with same mass

temperature decrease of *A* = temperature increase of *B*





Ideal Gas Bar Graph Solution

with same mass

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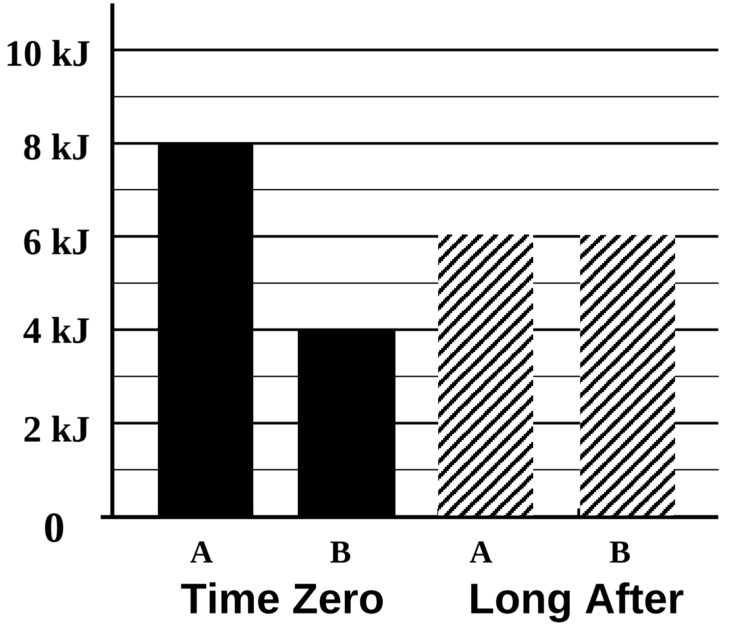
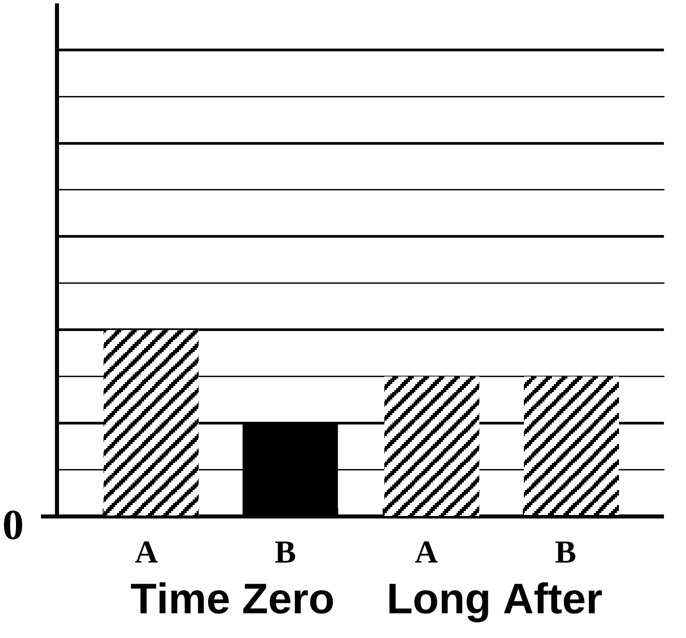
Internal Energy

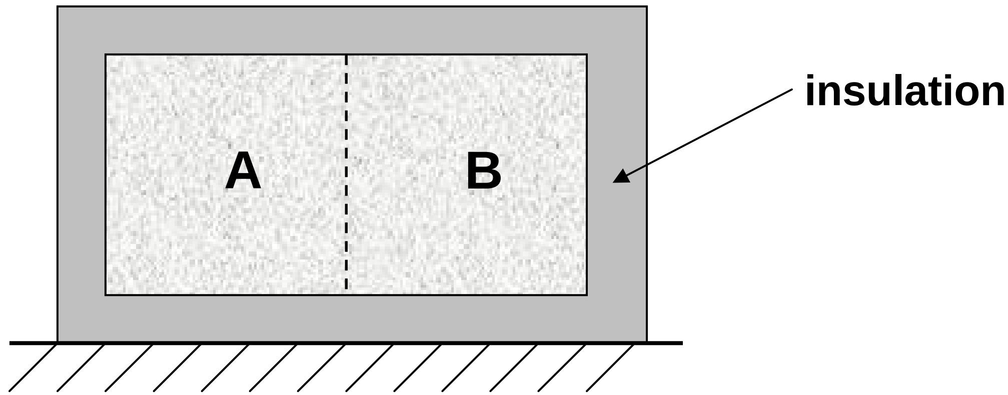


Absolute Temperature

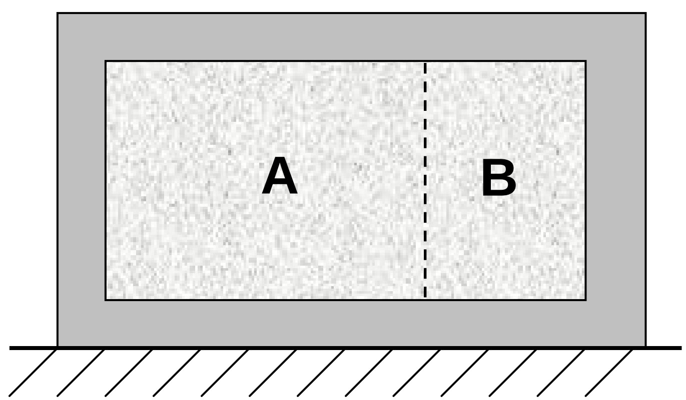


Problem Sequence

Ideal Gas with equal masses



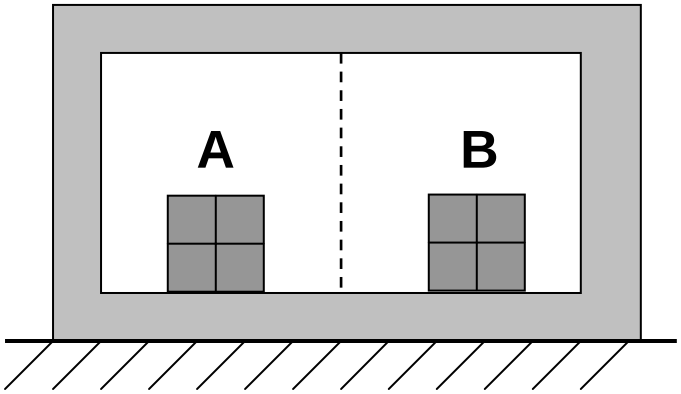
Ideal Gas, $m_A = 2m_B$



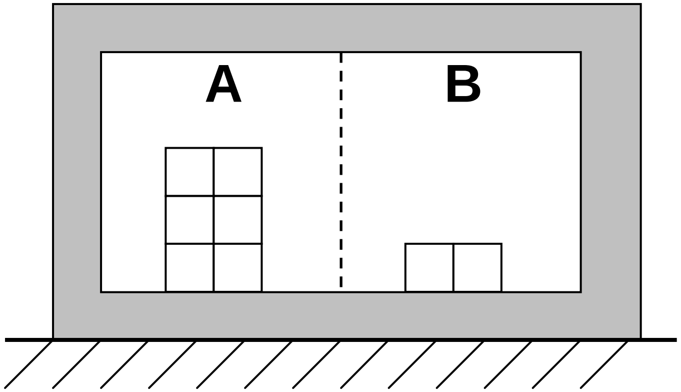
Change of Context

Problem: *A and B in thermal contact; given ΔT_A find ΔT_B.*

A and B are same material and have same masses, but have different initial temperatures

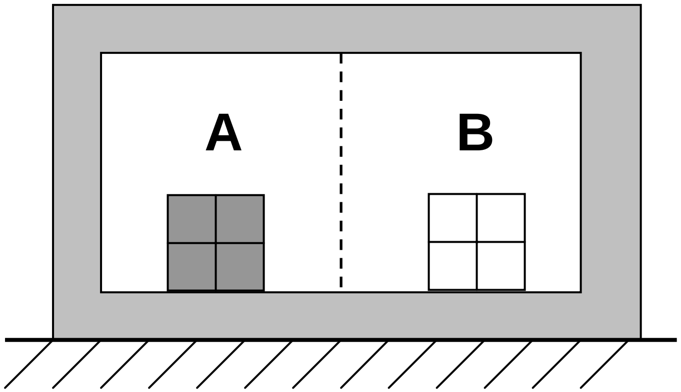


A and B are same material, have different initial temperatures, and $m_A = 3m_B$

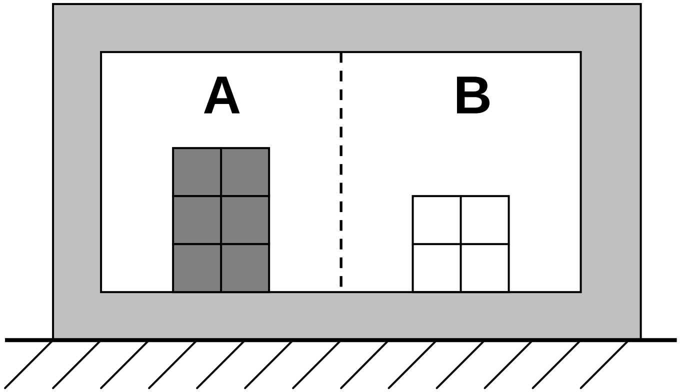


More examples

A and B are different materials with different initial temperatures, $c_A = 2c_B$ and $m_A = m_B$.



A and B are different materials with different initial temperatures, $c_A = 0.5c_B$ and $m_A = 1.5m_B$



Additional Resources

- *Physics by Inquiry*, Volume I, unit on "Heat and Temperature"
  - by Lillian C. McDermott and the Physics Education Group at the University of Washington; available from John Wiley
  - extensive set (≈ 40 pages) of guided-inquiry worksheets intended for small-group work in lab environment

Additional Resources

- *Tutorials in Introductory Physics*: tutorials on Ideal-Gas Law and First Law of Thermodynamics
  - by Lillian C. McDermott, Peter S. Shaffer, and the Physics Education Group
  - 3-5 page guided-inquiry worksheets for small-group use outside of lab setting
  - includes homework assignments, pretests, and exam questions
  - available from Prentice-Hall

Next Phase: Investigation of Student Reasoning in Thermodynamics

Research Basis for Curriculum Development *(NSF CCLI Project with T. Greenbowe)*

- Investigation of second-semester calculus-based physics course (mostly engineering students).

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- Detailed interviews (avg. duration ≥ one hour) carried out with 32 volunteers during 2002 (total class enrollment: 424).
  - *interviews carried out after all thermodynamics instruction completed*
  - *final grades of interview sample far above class average*

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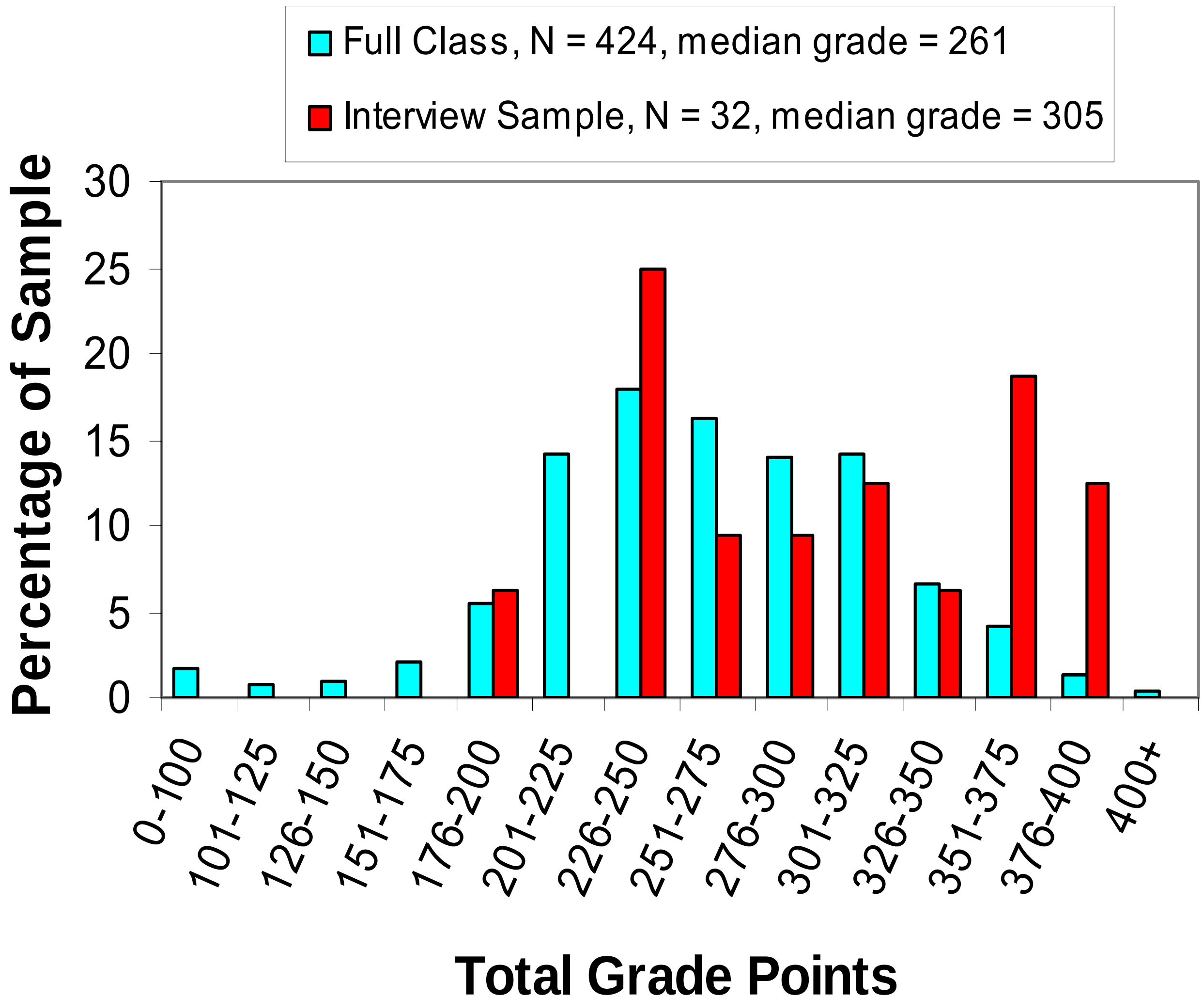
Grade Distributions: Interview Sample vs. Full Class



***Interview Sample*:**

34% above 91st percentile; 50% above 81st percentile

Student Understanding of Heat, Work, and the First Law of Thermodynamics

- Questions and problems focused on the first law of thermodynamics: $\Delta U = Q - W$

- Notation:

  ΔU =change in "internal" [thermal] energy of the system

  Q = heat transfer ***to*** the system

  W = work done ***by*** the system

- Internal energy is a *state function*, work and heat are *process-dependent* quantities

Predominant Themes of Students' Reasoning

1. Understanding of concept of state function in the context of energy.
2. Belief that work is a state function.
3. Belief that heat is a state function.
4. Belief that net work done and net heat transferred during a cyclic process are zero.
5. Inability to apply the first law of thermodynamics.

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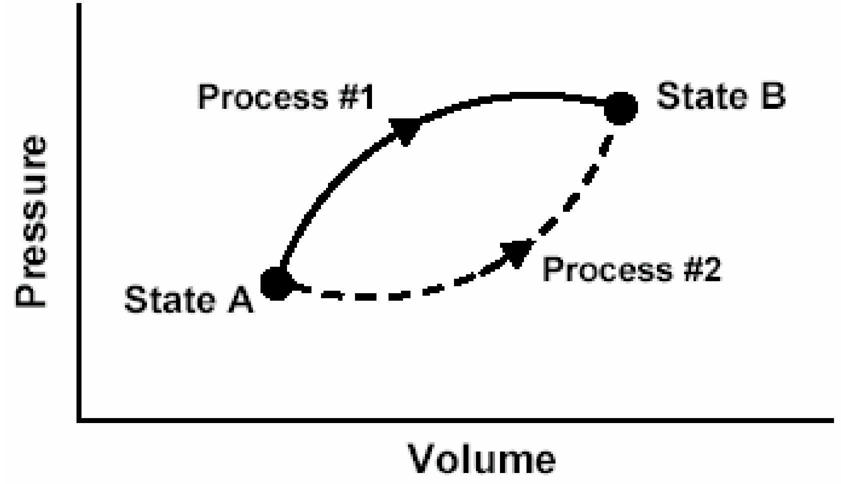
Understanding of Concept of State Function in the Context of Energy

- Diagnostic question: two different processes connecting identical initial and final states.
- Do students realize that only initial and final states determine change in a state function?

This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:



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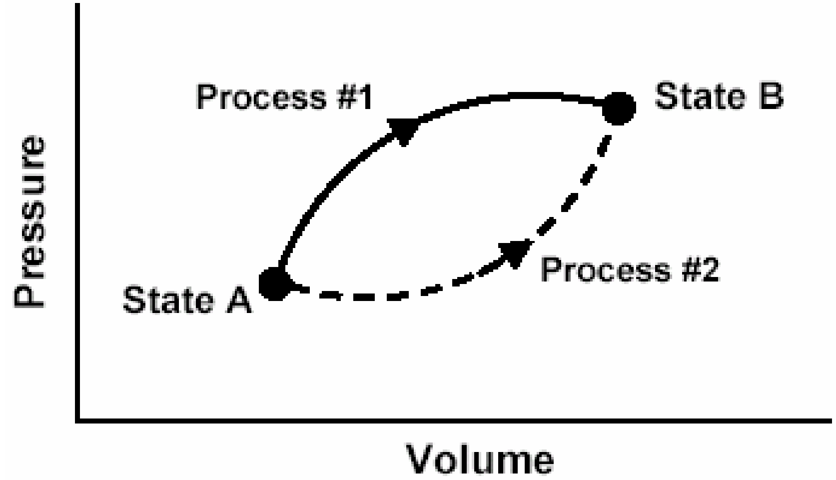

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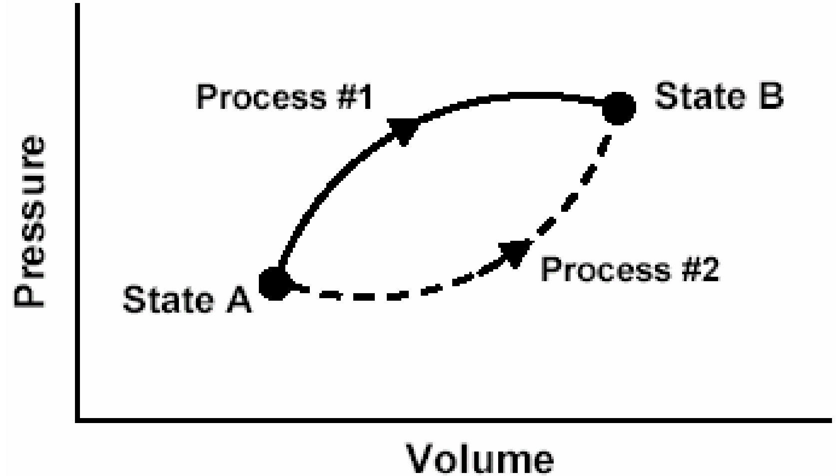

[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

1. Is *W* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2? Explain.

2. Is *Q* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2?

3. Which would produce the largest change in the total energy of all the atoms in the system: ***Process #1, Process #2,*** or ***both processes produce the same change?***

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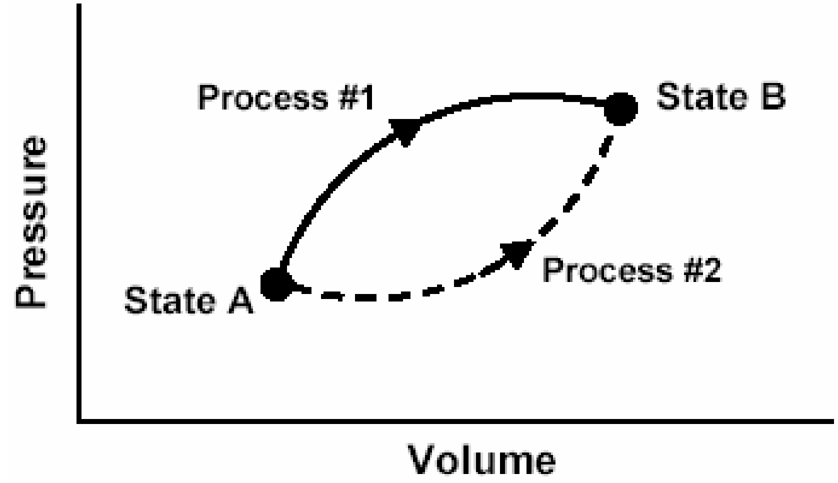

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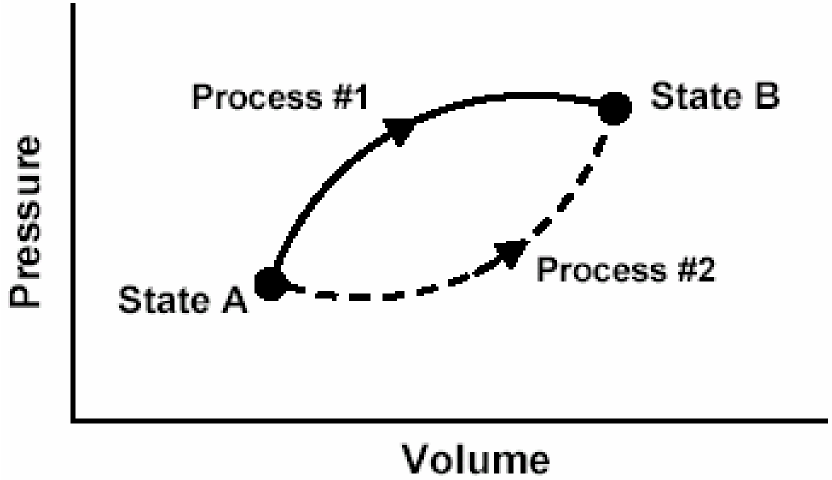
$\Delta U_1 = \Delta U_2$



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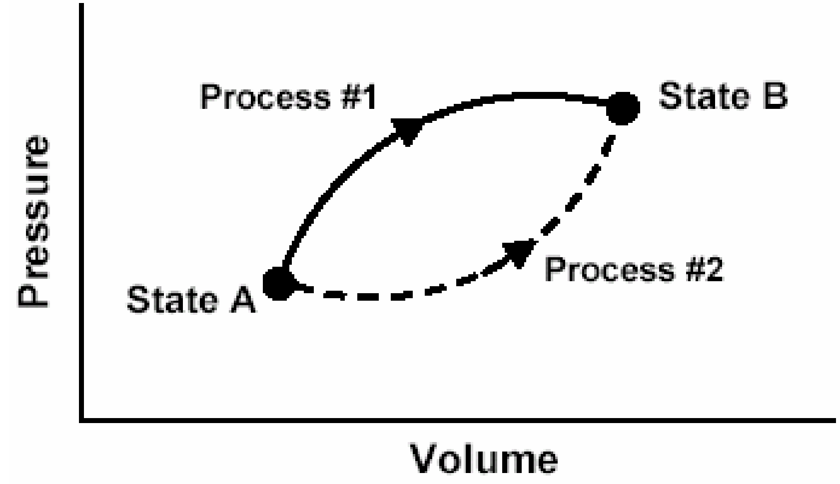

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➡ Students' major conceptual difficulties stemmed from ***overgeneralization*** of state-function concept.

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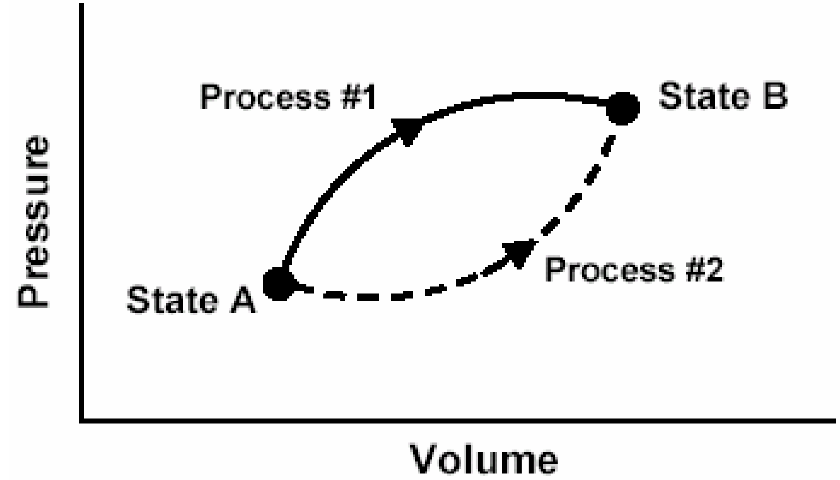

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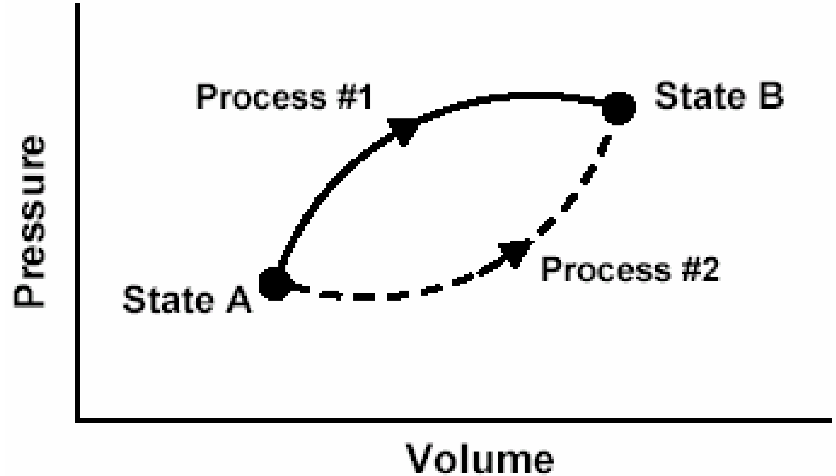

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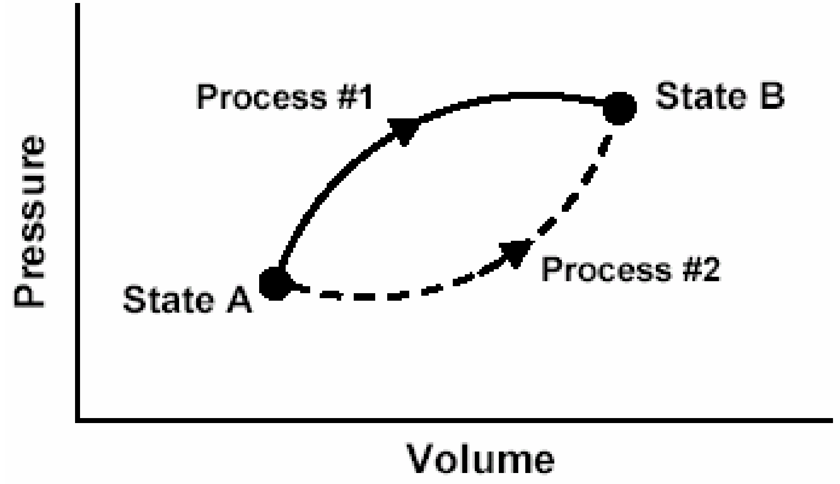

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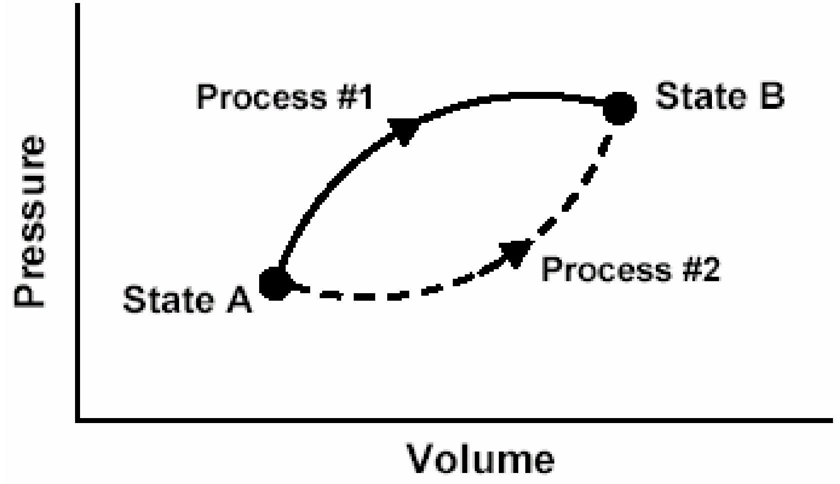

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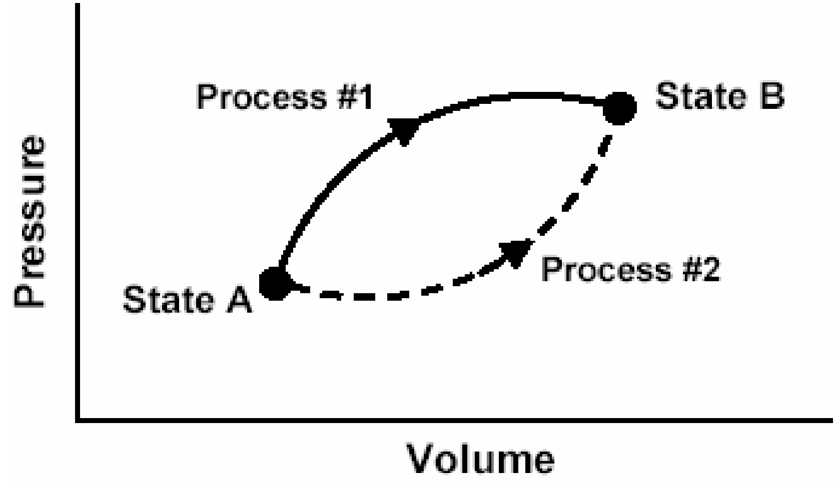

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Responses to Diagnostic Question #1
(Work question)

	1999 **(*N*=186)**	**2000** **(*N*=188)**	**2001** **(*N*=279)**	**2002** **Interview Sample** **(*N*=32)**
$W_1 > W_2$				
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Because work is independent of path	*	14%	23%	22%
Other reason, or none	*	12%	13%	0%

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Explanations Given by Interview Subjects to Justify $W_1 = W_2$

- "*Work is a state function*."
- "*No matter what route you take to get to state B from A, it's still the same amount of work*."
- "*For work done take state A minus state B; the process to get there doesn't matter*."

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Confusion with mechanical work done by conservative forces?

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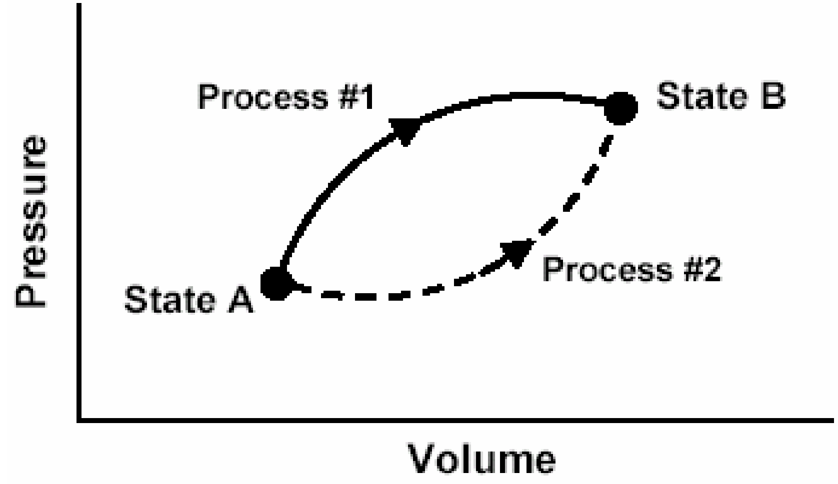

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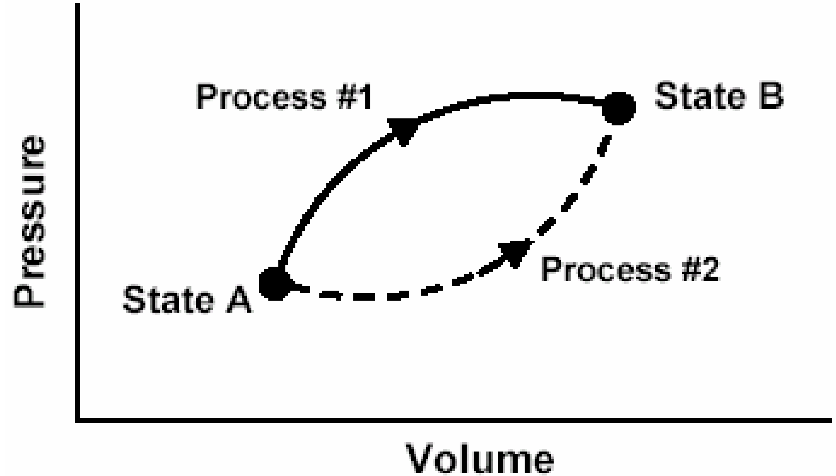

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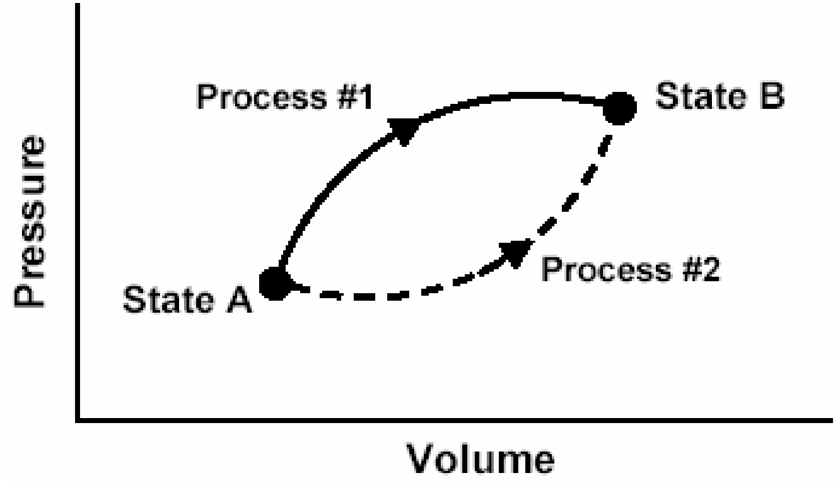

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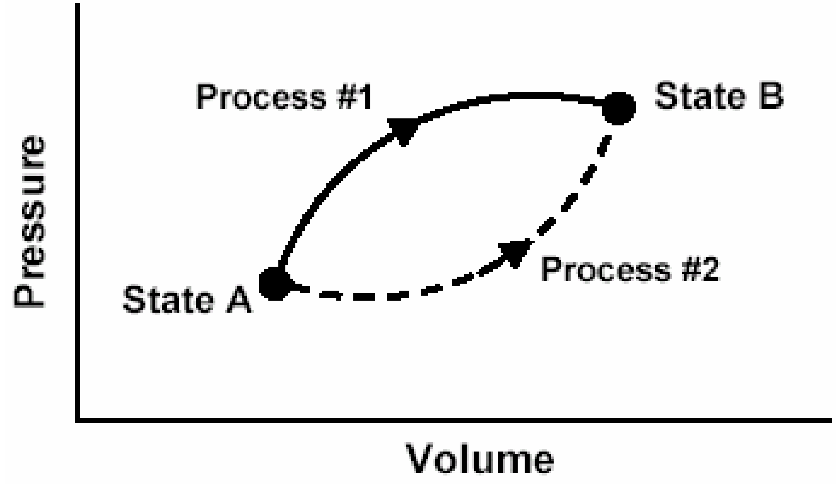

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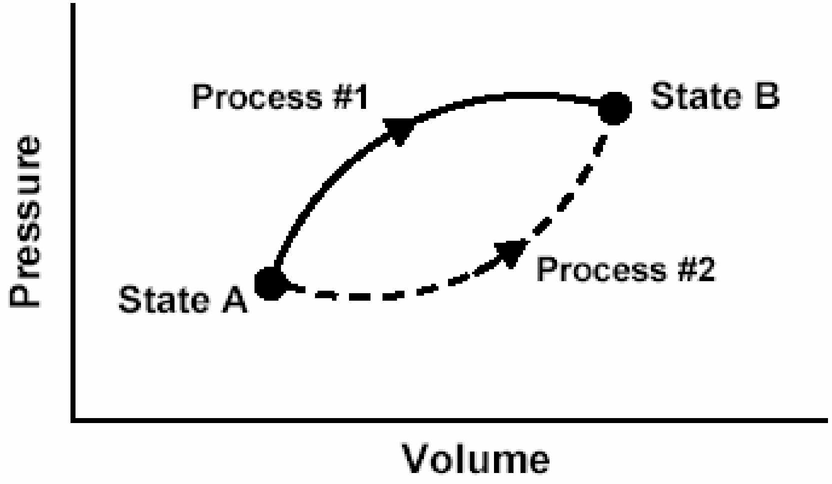

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$Q_1 = Q_2$	**31%**	**43%**	**41%**	**47%**

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(Heat question)

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$Q_1 = Q_2$	**31%**	**43%**	**41%**	**47%**
Because heat is independent of path	**21%**	**23%**	**20%**	**44%**

Responses to Diagnostic Question #2
(Heat question)

	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
$Q_1 = Q_2$	**31%**	**43%**	**41%**	**47%**
Because heat is independent of path	**21%**	**23%**	**20%**	**44%**
Other explanation, or none	**10%**	**18%**	**20%**	**3%**

Explanations Given by Interview Subjects to Justify $Q_1 = Q_2$

- "*I believe that heat transfer is like energy in the fact that it is a state function and doesn't matter the path since they end at the same point*."
- "*Transfer of heat doesn't matter on the path you take*."
- "*They both end up at the same PV value so . . . They both have the same Q or heat transfer*."

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Interview Questions

A fixed quantity of ideal gas is contained within a metal cylinder that is sealed with a movable, frictionless, insulating piston.

The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

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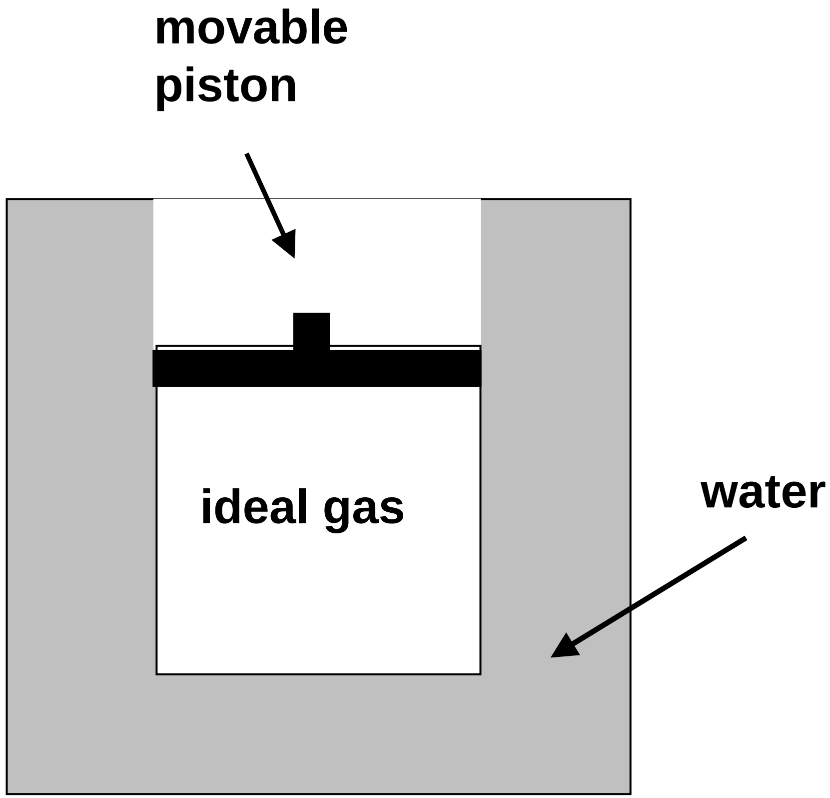
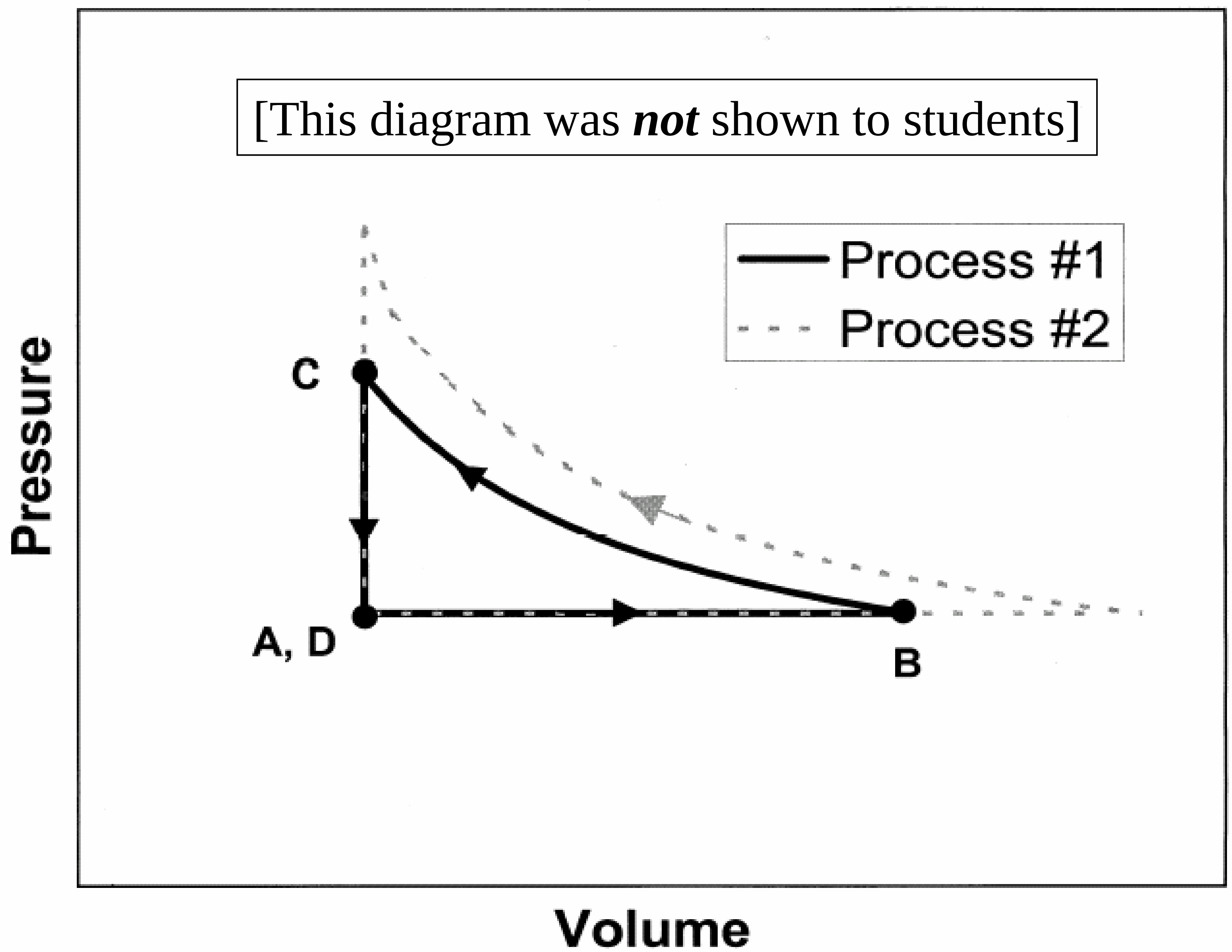
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

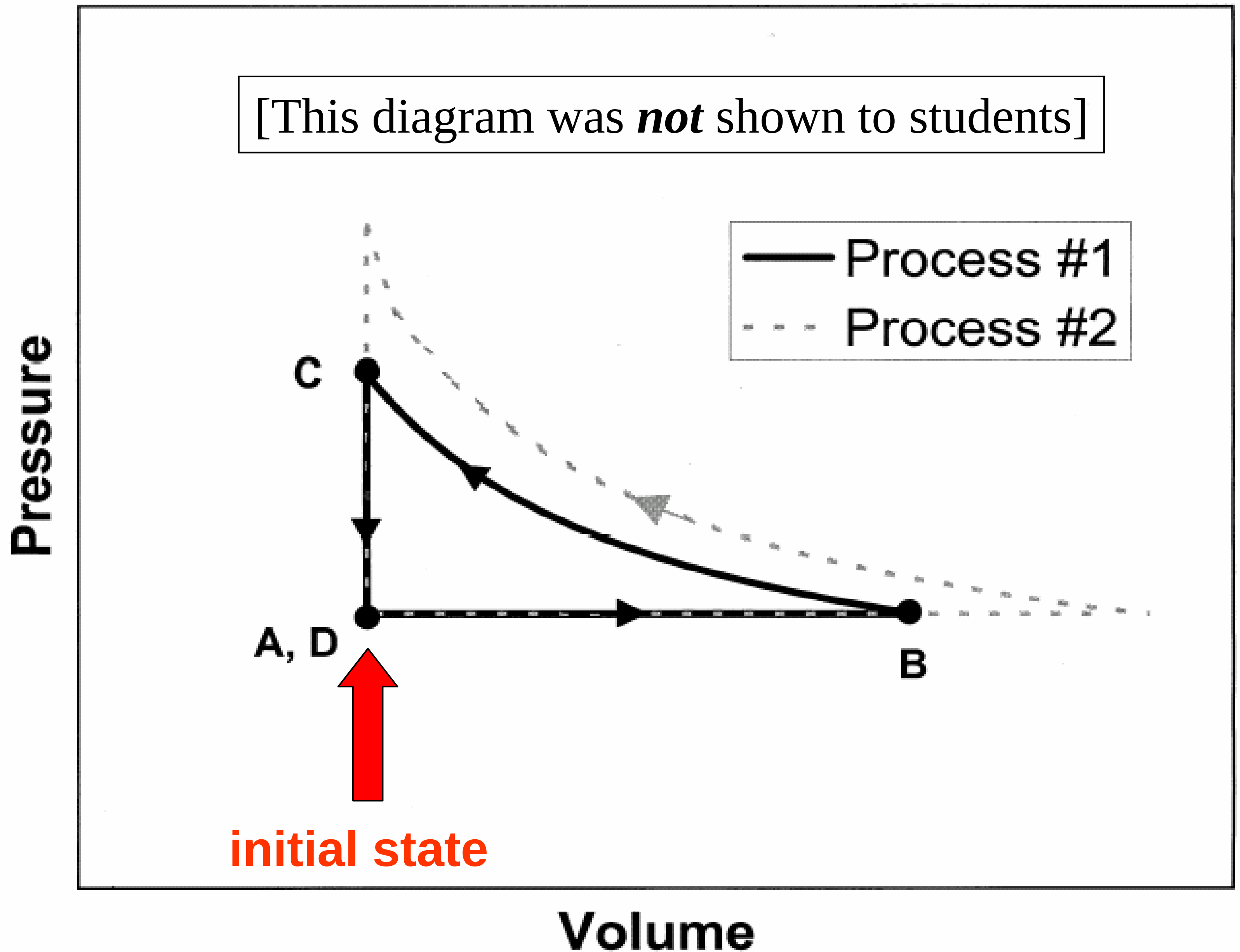
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature



Time *A*

Entire system at room temperature.


[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume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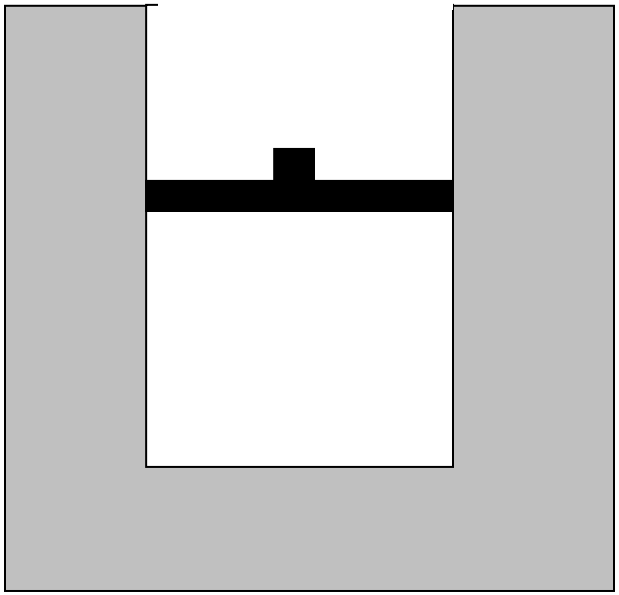
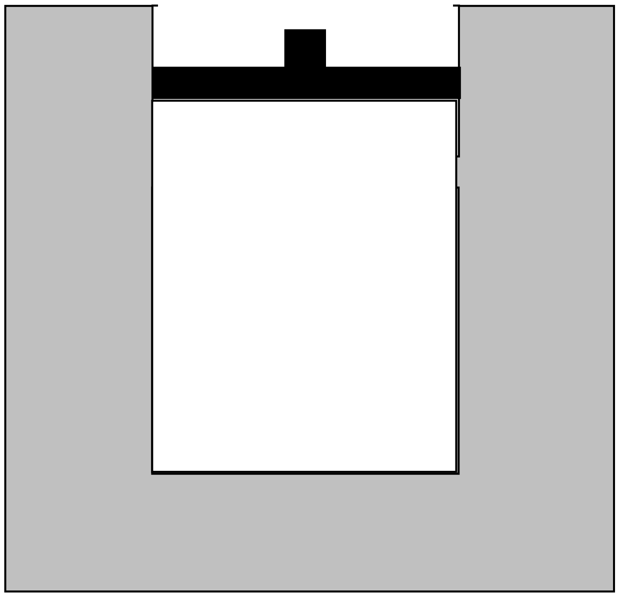
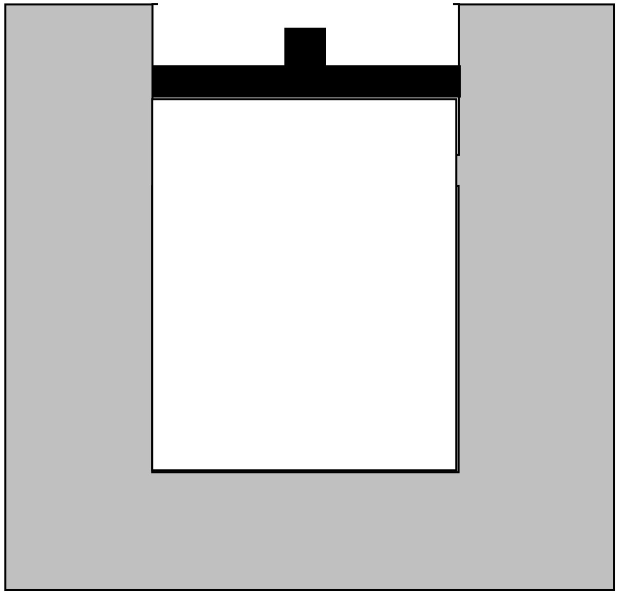
Process #2
C
A, D
B
initial state
Pressure
Volume

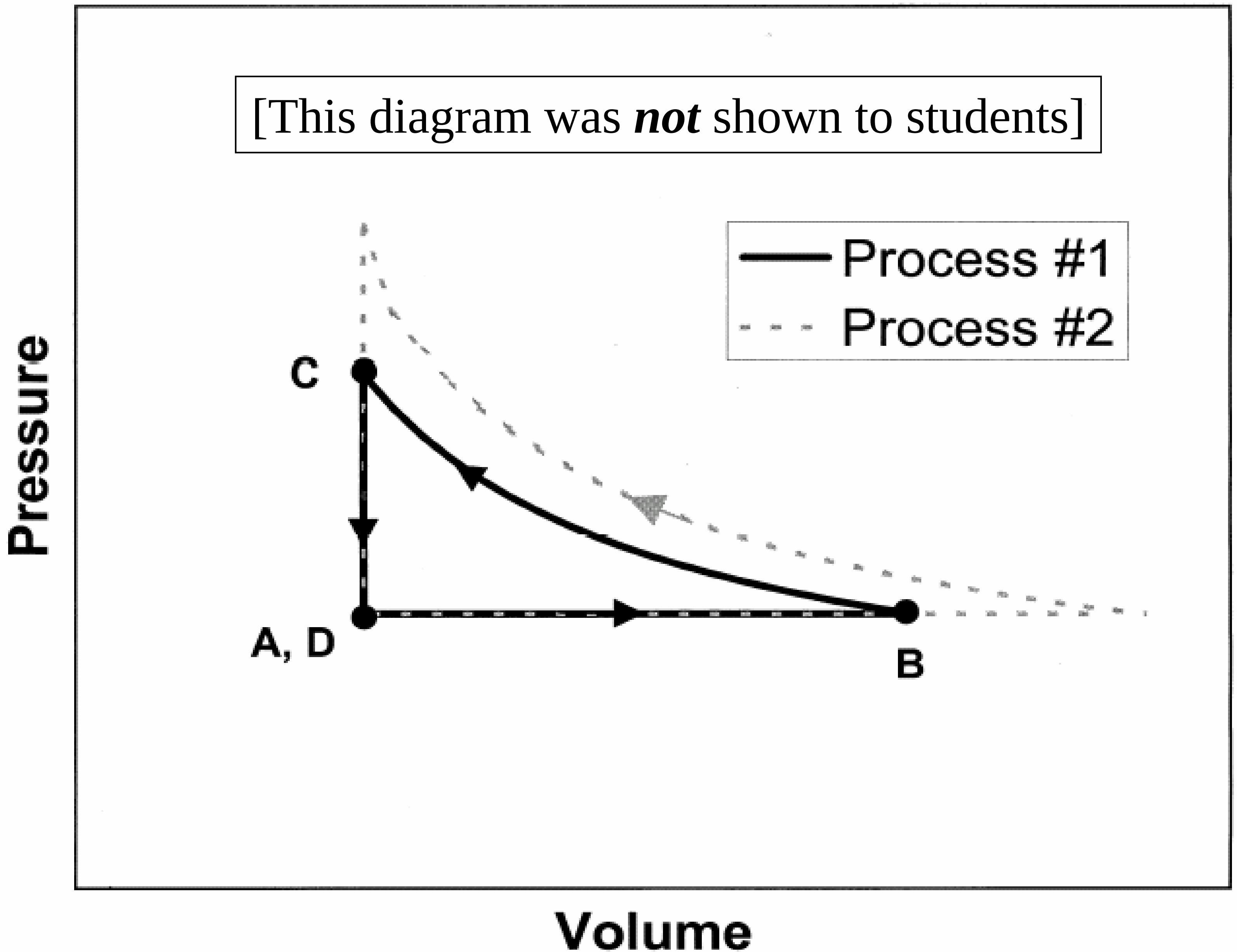
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.





At time ***B*** the heating of the water stops, and the piston stops moving





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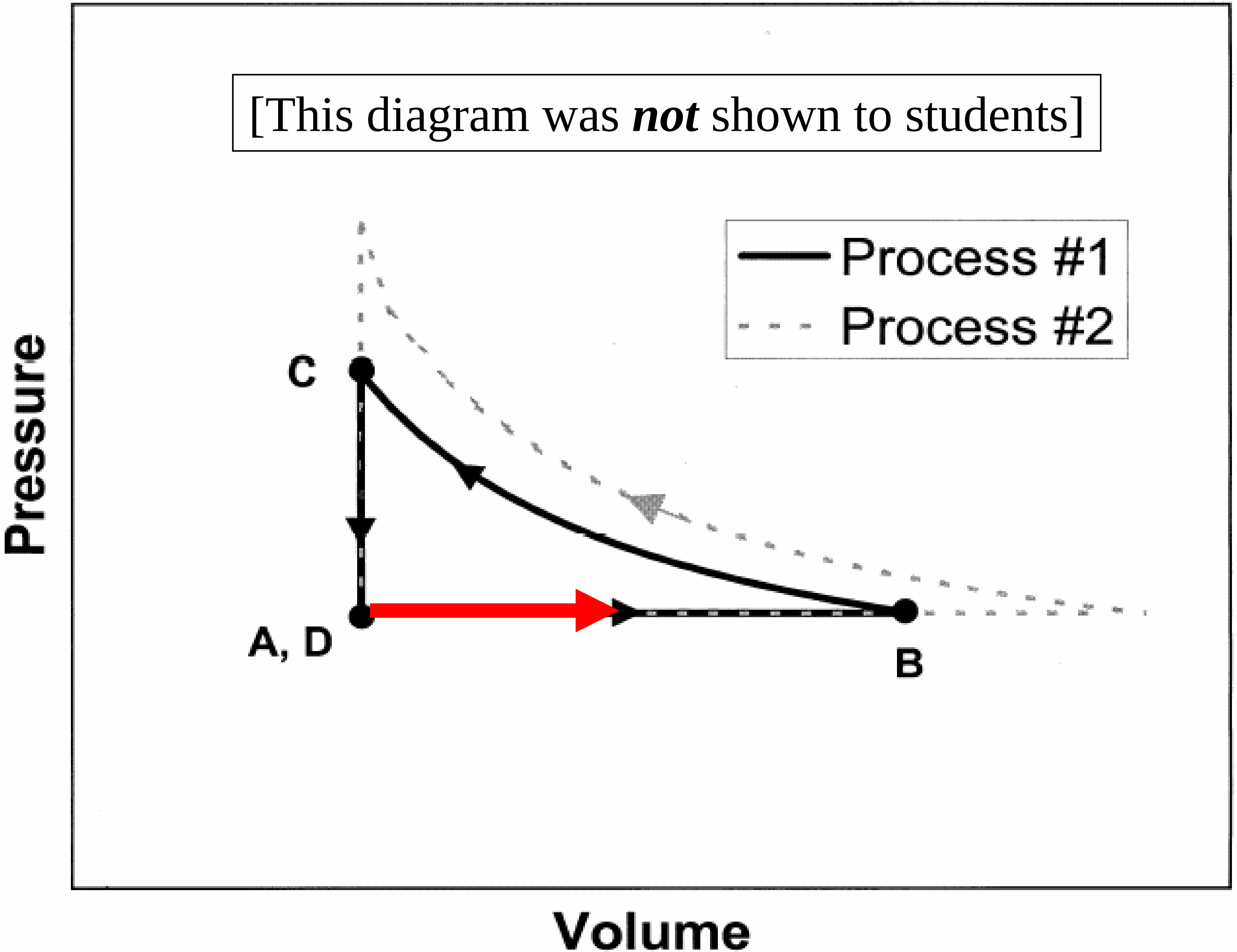
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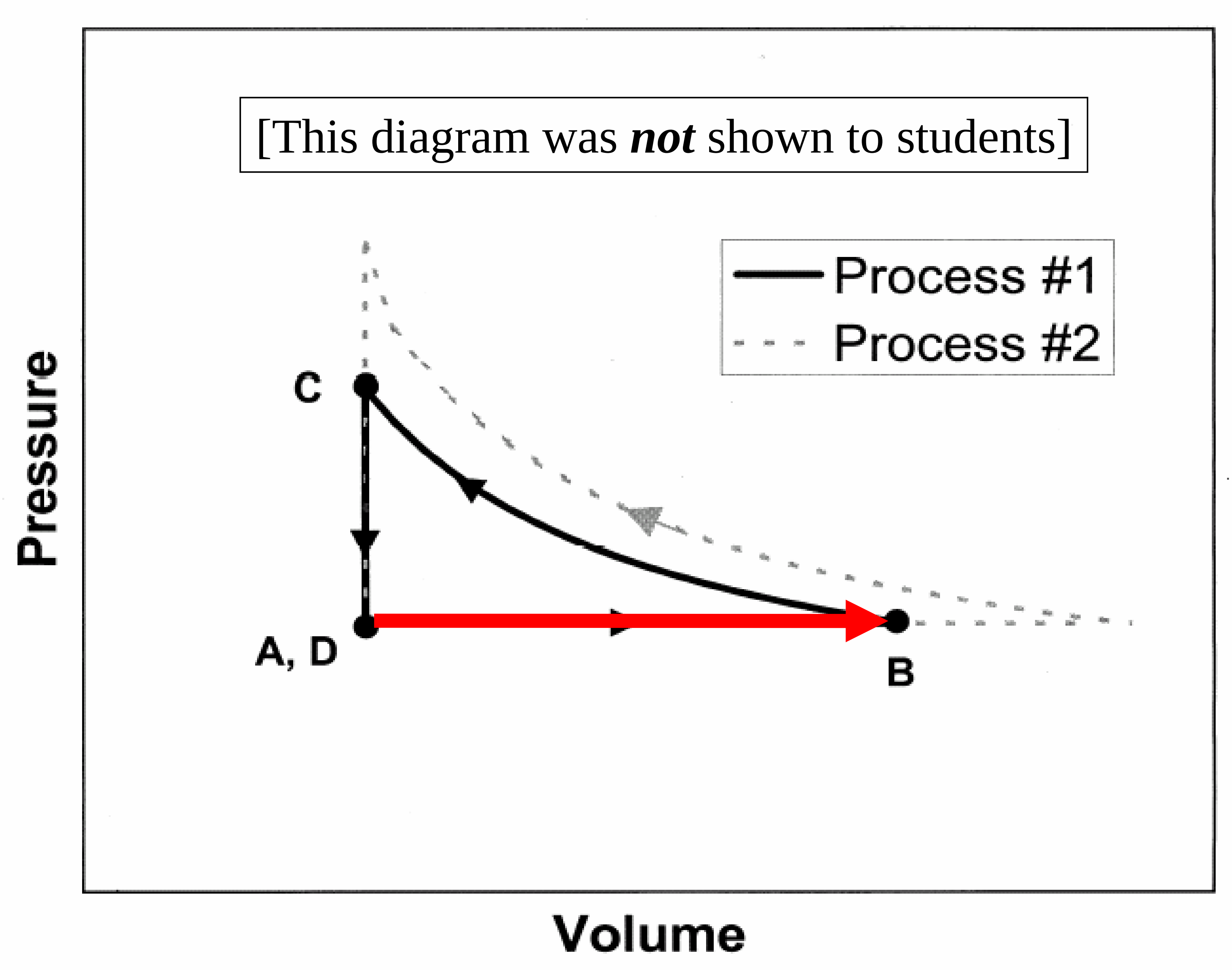
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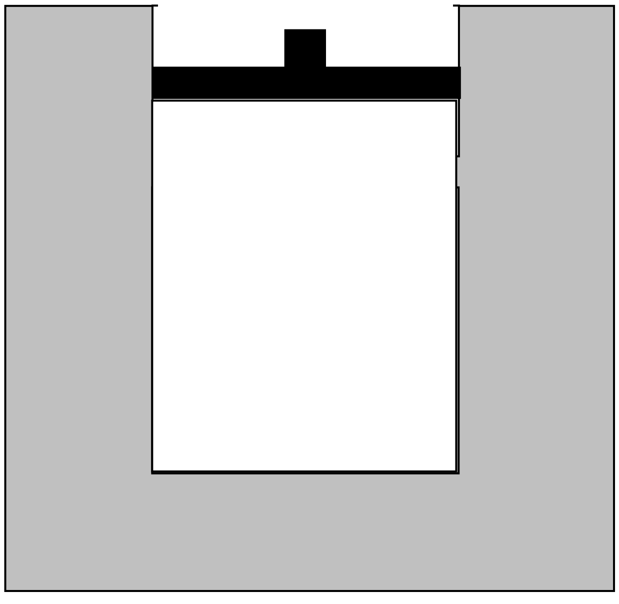

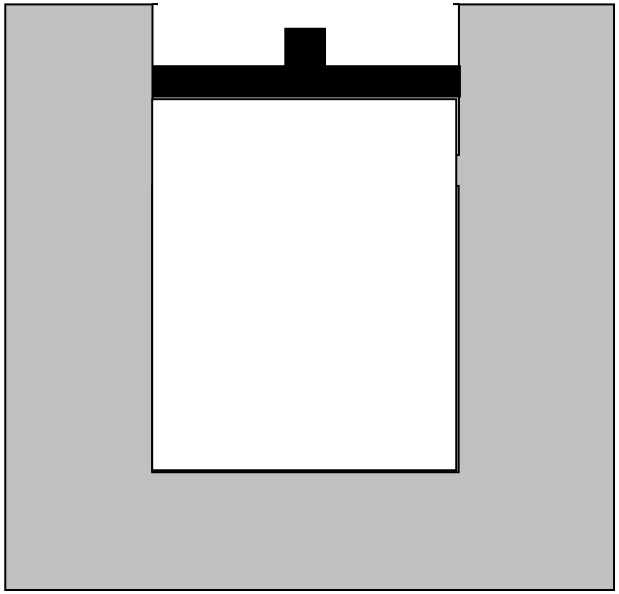

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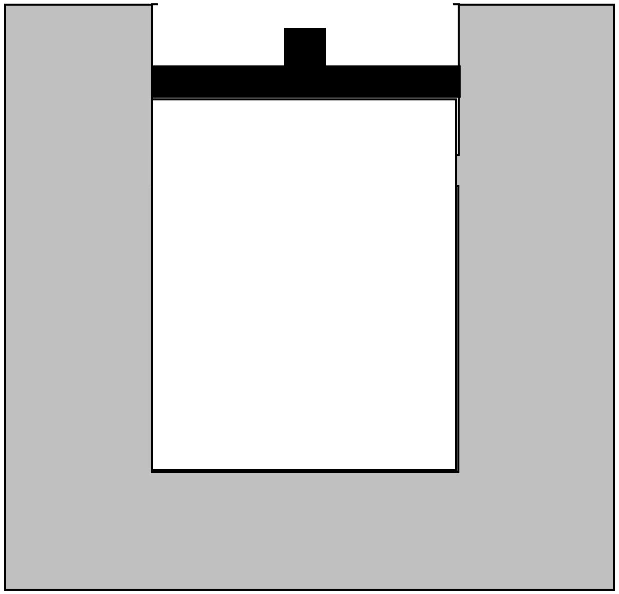

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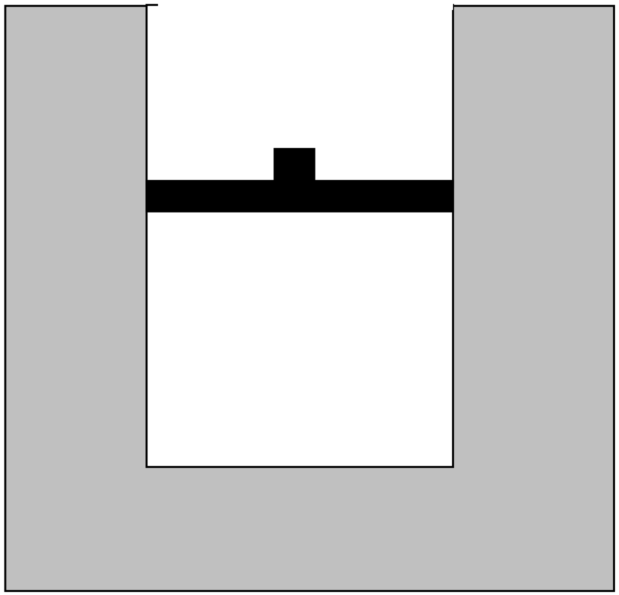
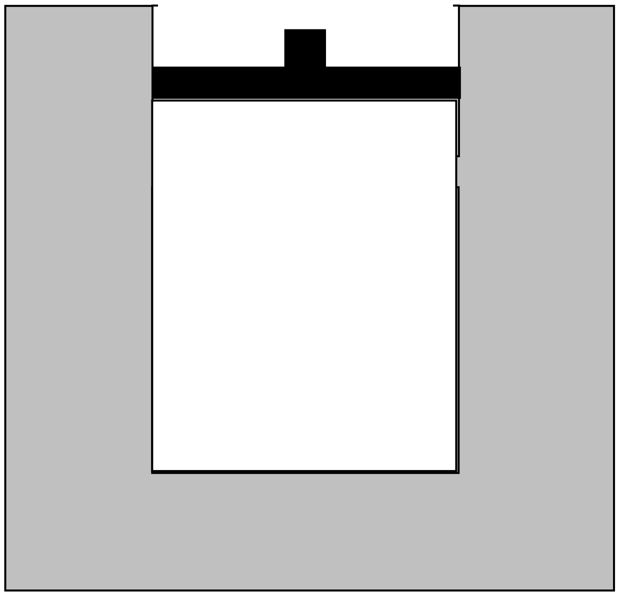
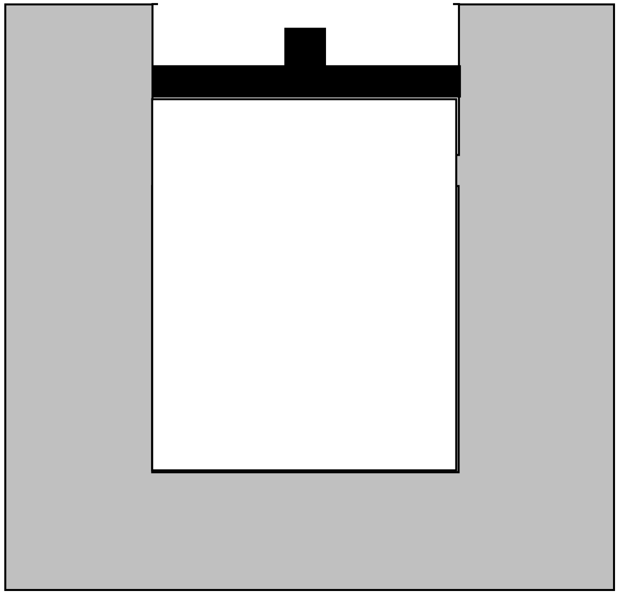
Failure to Recognize “Work” as a Mechanism of Energy Transfer

- Basic notion of thermodynamics: if part or all of system boundary is displaced during quasistatic process, energy is transferred between system and surroundings in the form of “work.”
- Study of Loverude, Kautz, and Heron (2002) showed that few students could spontaneously invoke concept of work in case of adiabatic compression.
- Present investigation probed student reasoning regarding work in case of isobaric expansion and isothermal compression.







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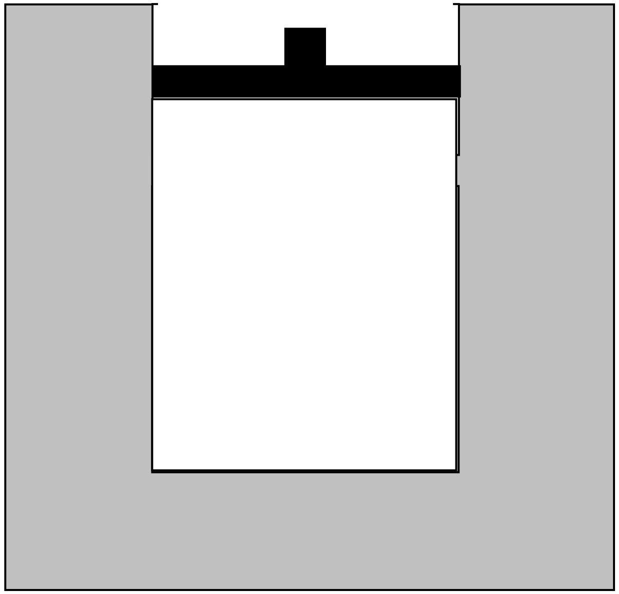

Question #1: During the process that occurs from time *A* to time *B*, which of the following is true: (a) positive work is done *on* the gas *by* the environment, **(b) positive work is done *by* the gas *on* the environment,** (c) no *net* work is done on or by the gas.

Results on Question #1

(a) positive work done *on* gas *by* environment:
31%

(b) positive work done *by* gas *on* environment *[correct]:*
69%

Sample explanations for (a) answer:

"The water transferred heat to the gas and expanded it, so work was being done to the gas to expand it."

"The environment did work on the gas, since it made the gas expand and the piston moved up . . . water was heating up, doing work on the gas, making it expand."

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"The environment did work on the gas, since it made the gas expand and the piston moved up . . . water was heating up, doing work on the gas, making it expand."

Many students employ the term "work" to describe a heating process.

Results on Question #1

(a) positive work done *on* gas *by* environment:
31%

(b) positive work done *by* gas *on* environment *[correct]:*
69%

Sample explanations for (a) answer:

"The water transferred heat to the gas and expanded it, so work was being done to the gas to expand it."

"The environment did work on the gas, since it made the gas expand and the piston moved up . . . water was heating up, doing work on the gas, making it expand."

→ *Nearly one third of the interview sample believe that environment does positive work* **on** *gas during expansion.*

Results on Question #1

(a) positive work done *on* gas *by* environment:
31%

(b) positive work done *by* gas *on* environment *[correct]:*
69%

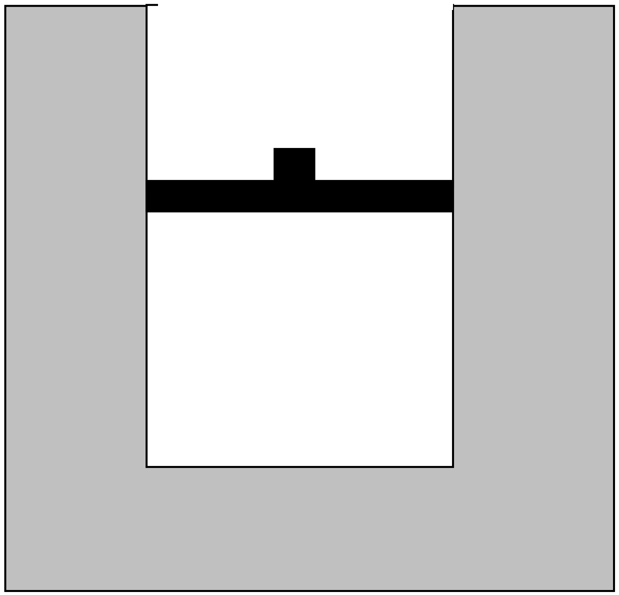
Sample explanations for (a) answer:

"The water transferred heat to the gas and expanded it, so work was being done to the gas to expand it."

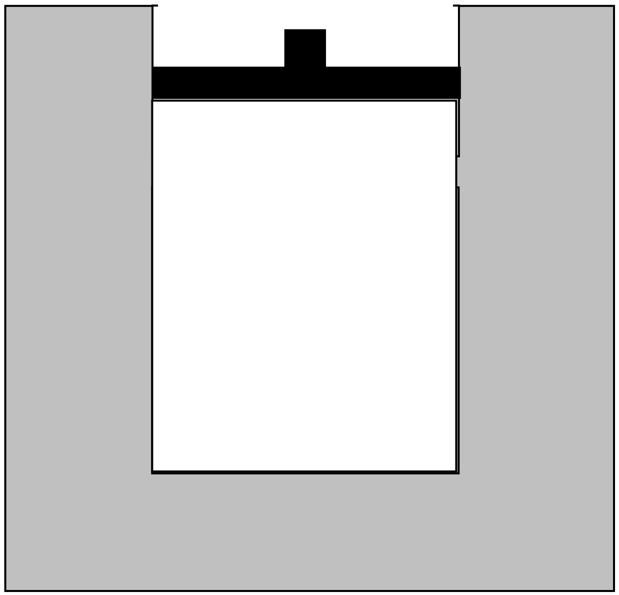
"The environment did work on the gas, since it made the gas expand and the piston moved up . . . water was heating up, doing work on the gas, making it expand."

Additional questions showed that half the sample did not realize that some energy was transferred away from gas due to expansion.

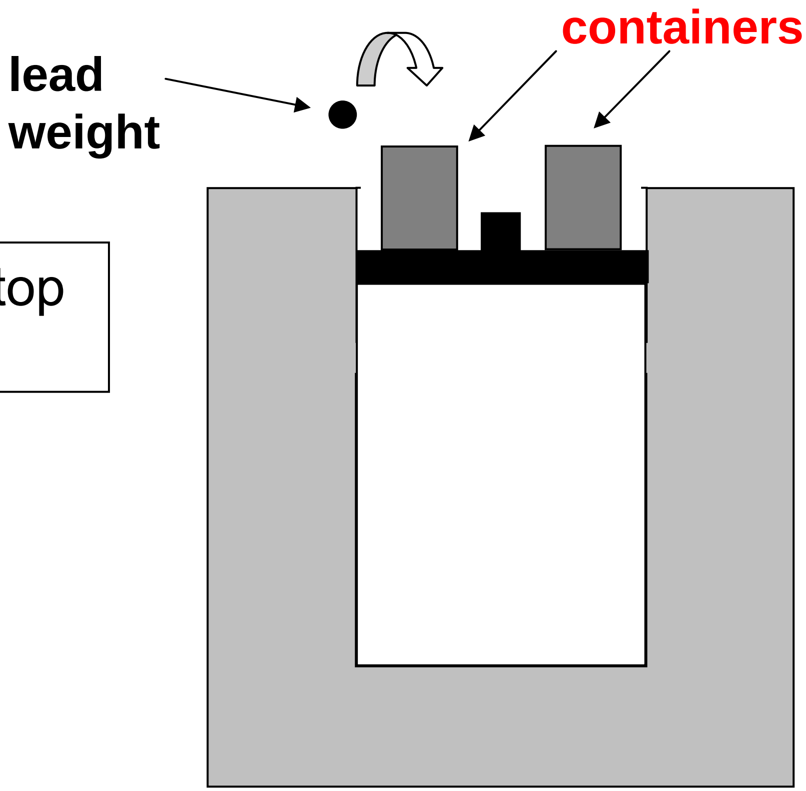
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.



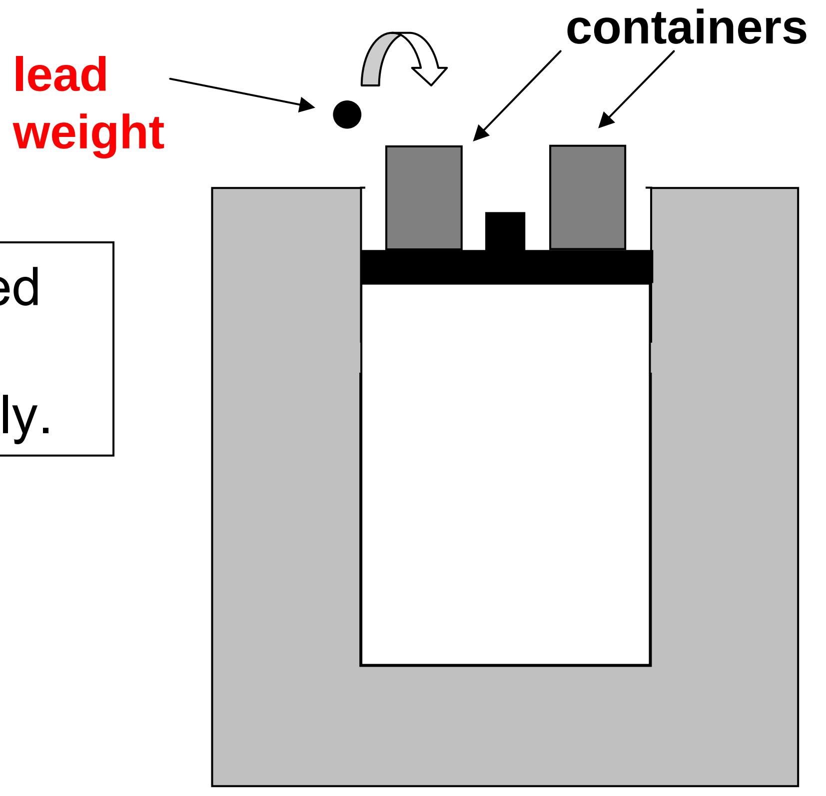
At time ***B*** the heating of the water stops, and the piston stops moving

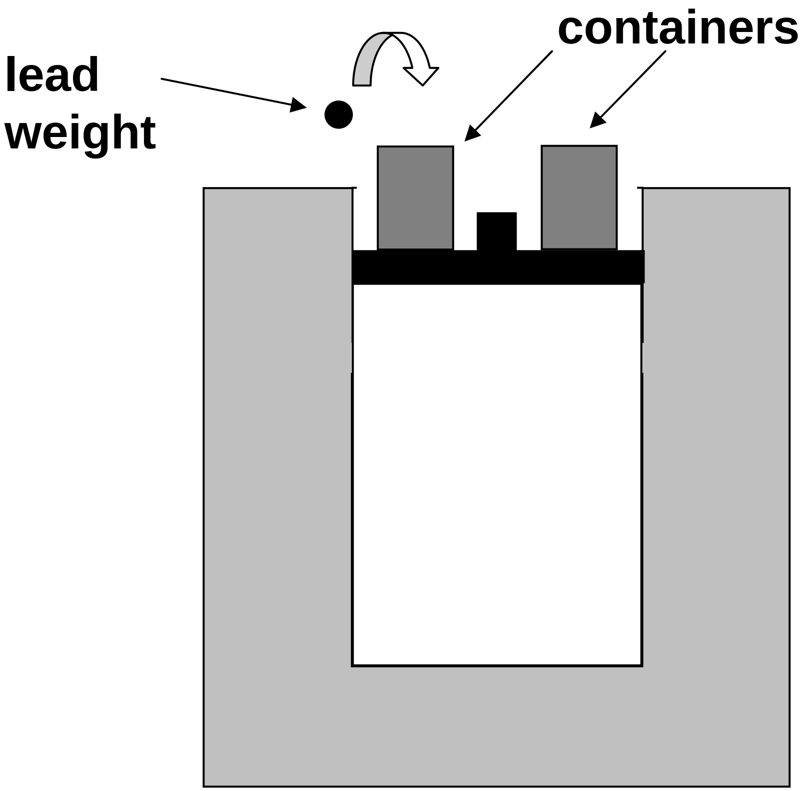


Now, empty containers are placed on top of the piston as shown.

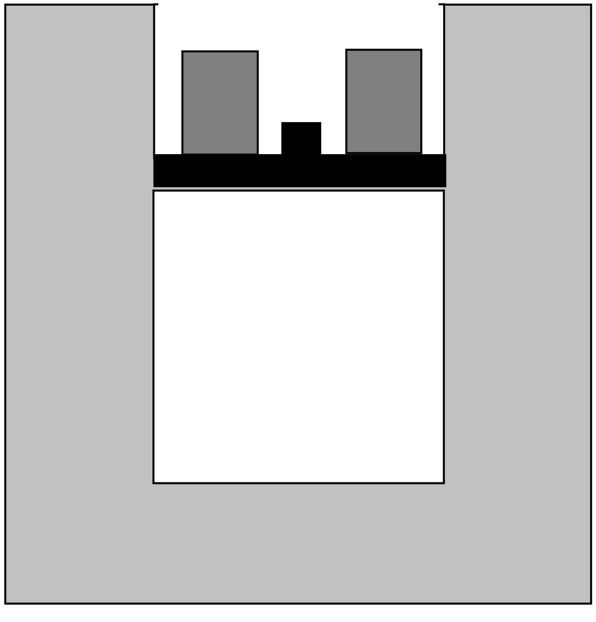


Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly.

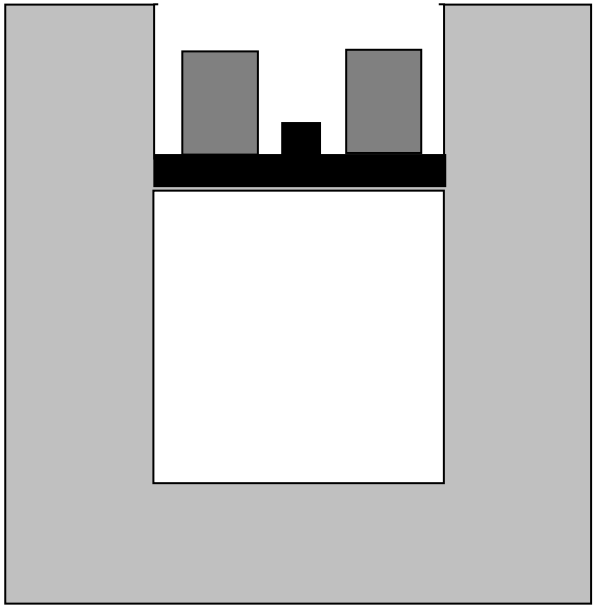




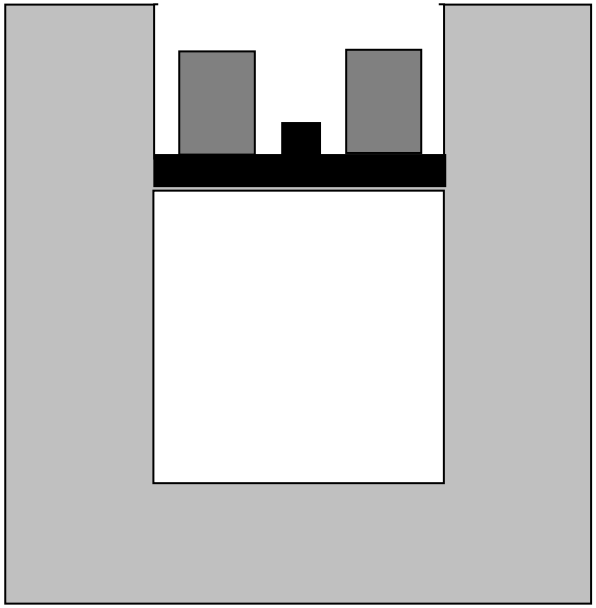
lead weight
containers

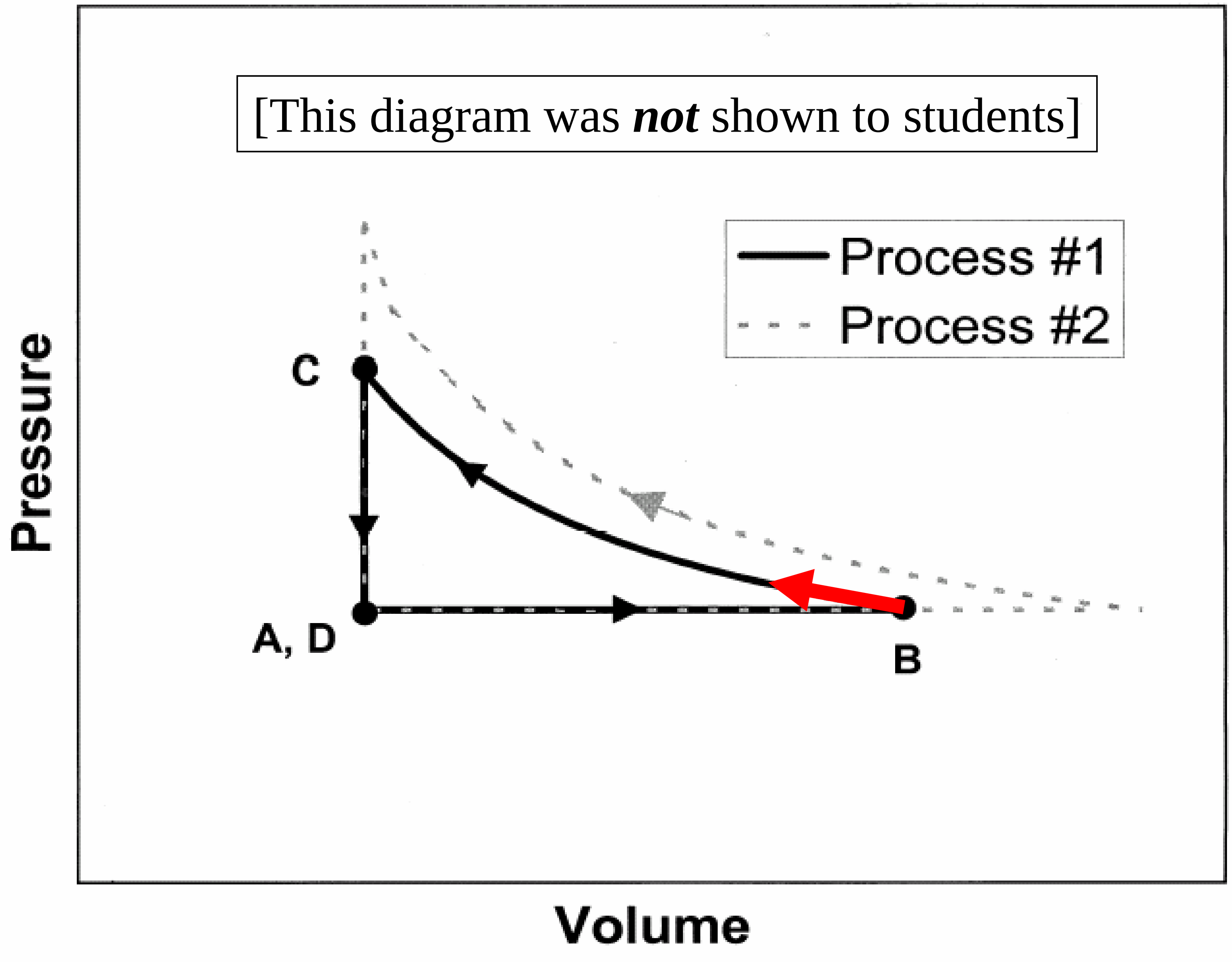


While this happens the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*.

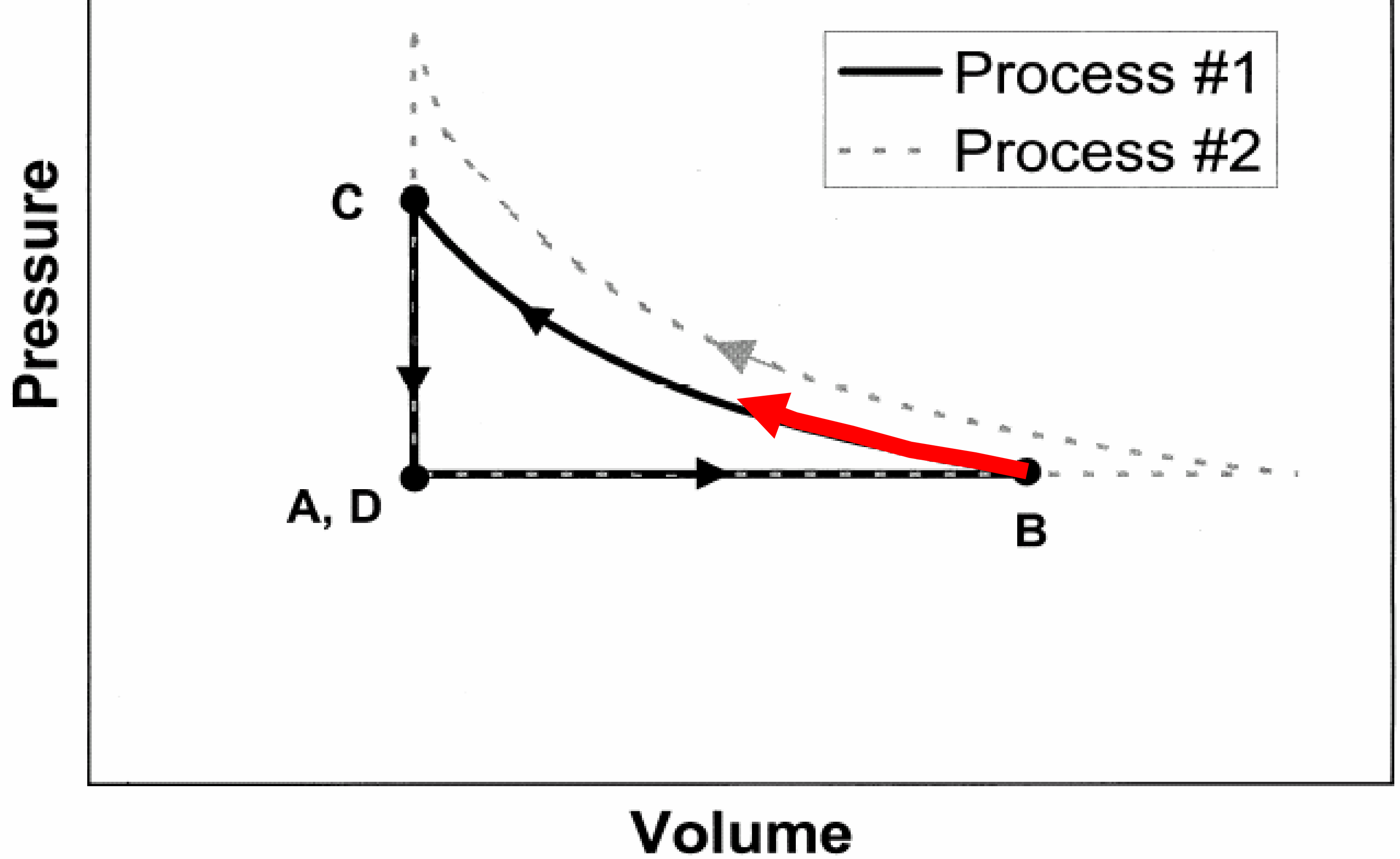


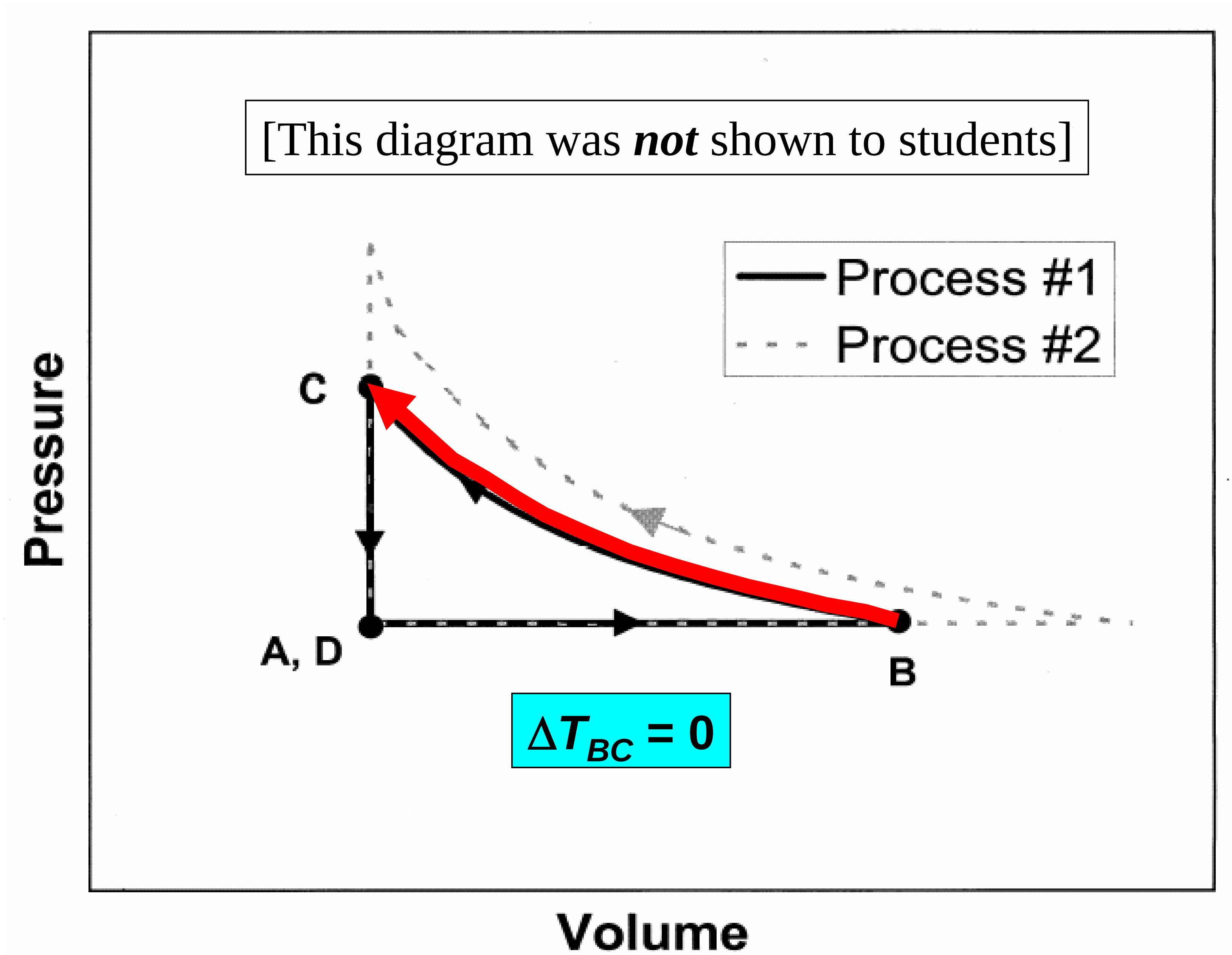
At time ***C*** we stop adding lead weights to the container and the piston stops moving. The piston is now at exactly the same position it was at time ***A*** .

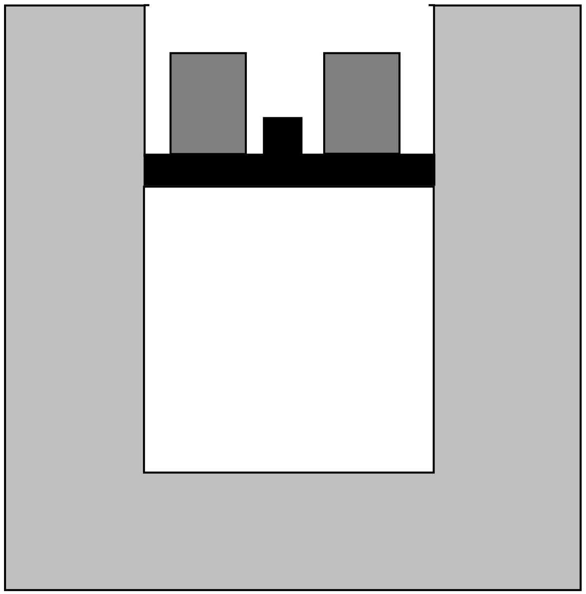



[This diagram was not shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

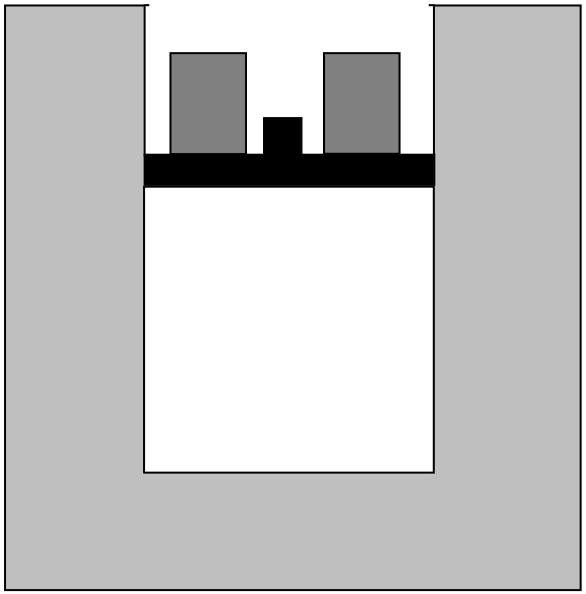
[This diagram was ***not*** shown to students]




[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
$\Delta T_{BC} = 0$
Pressure
Volume



Question #4: During the process that occurs from time *B* to time *C*, is there *any* net energy flow between the gas and the water? If no, explain why not. If yes, is there a net flow of energy from gas to water, or from water to gas?



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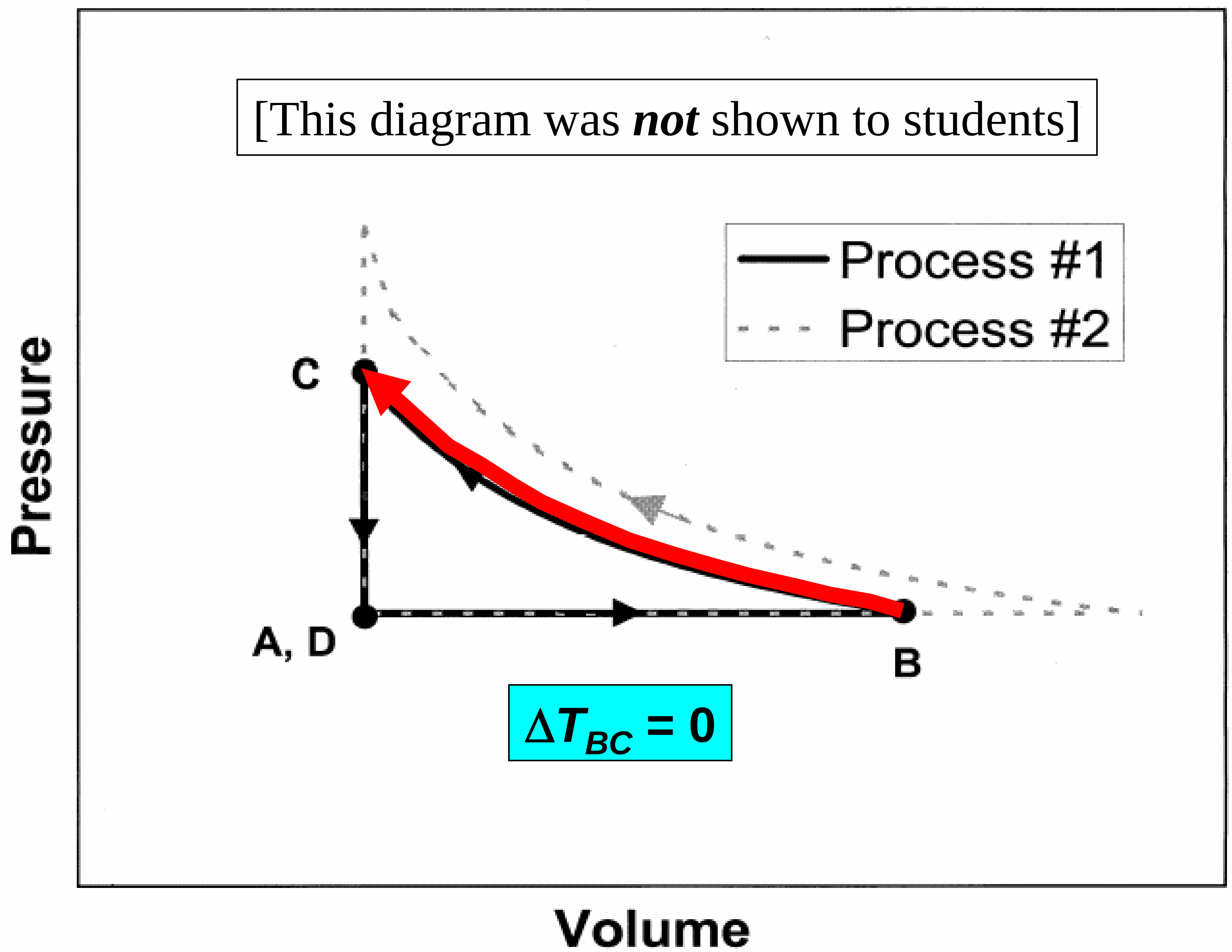
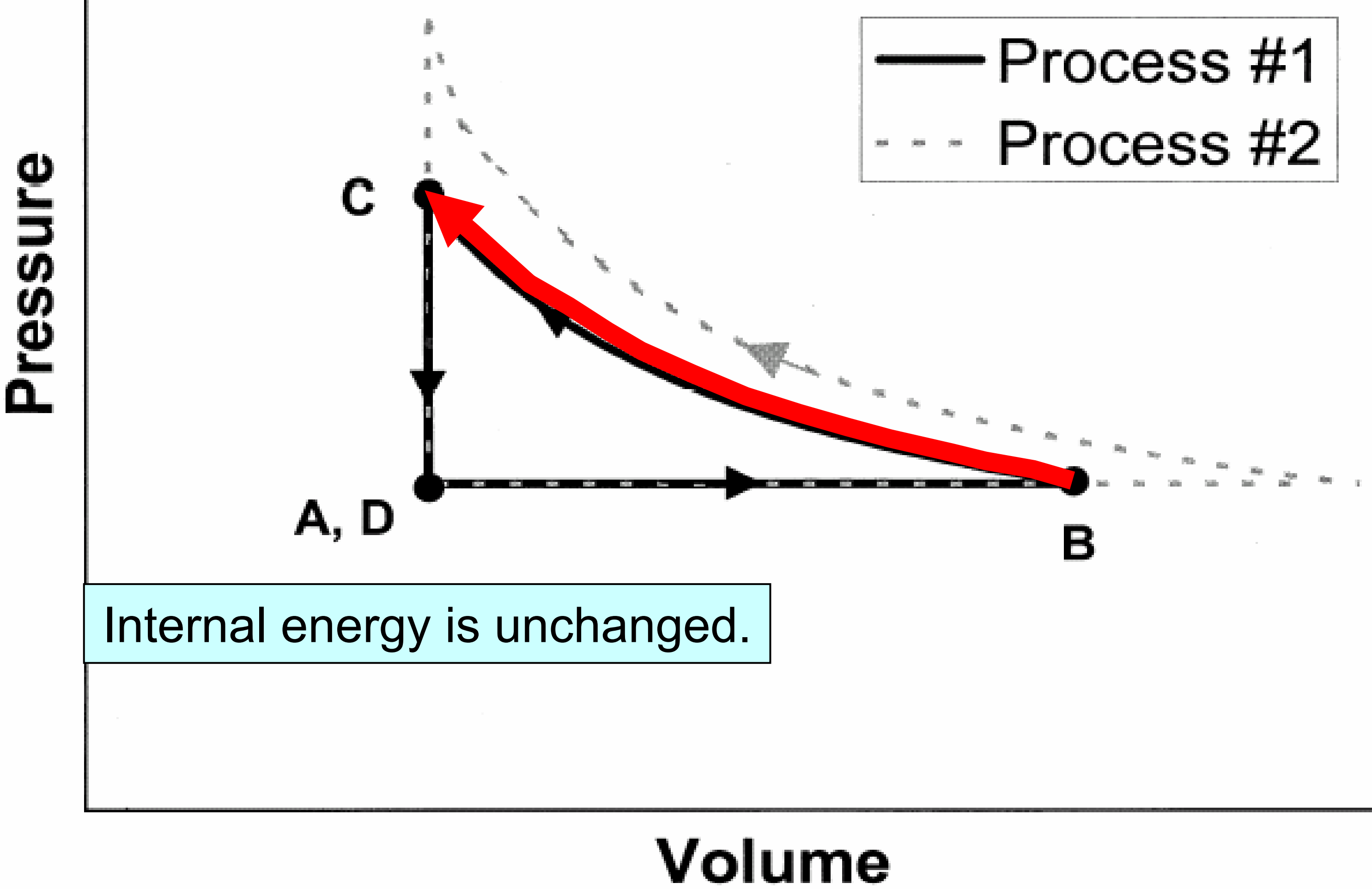
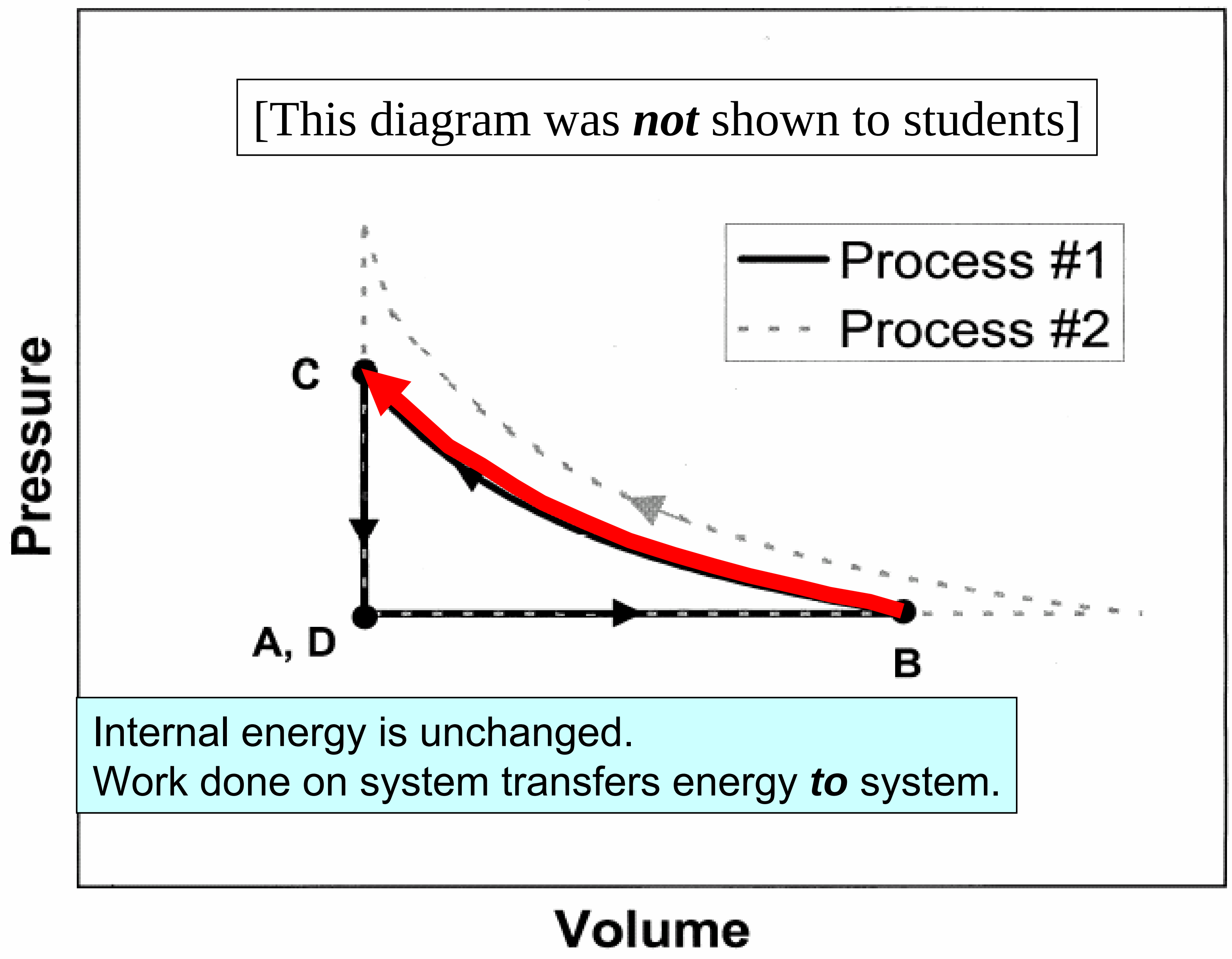

[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
$\Delta T_{BC} = 0$
Pressure
Volume

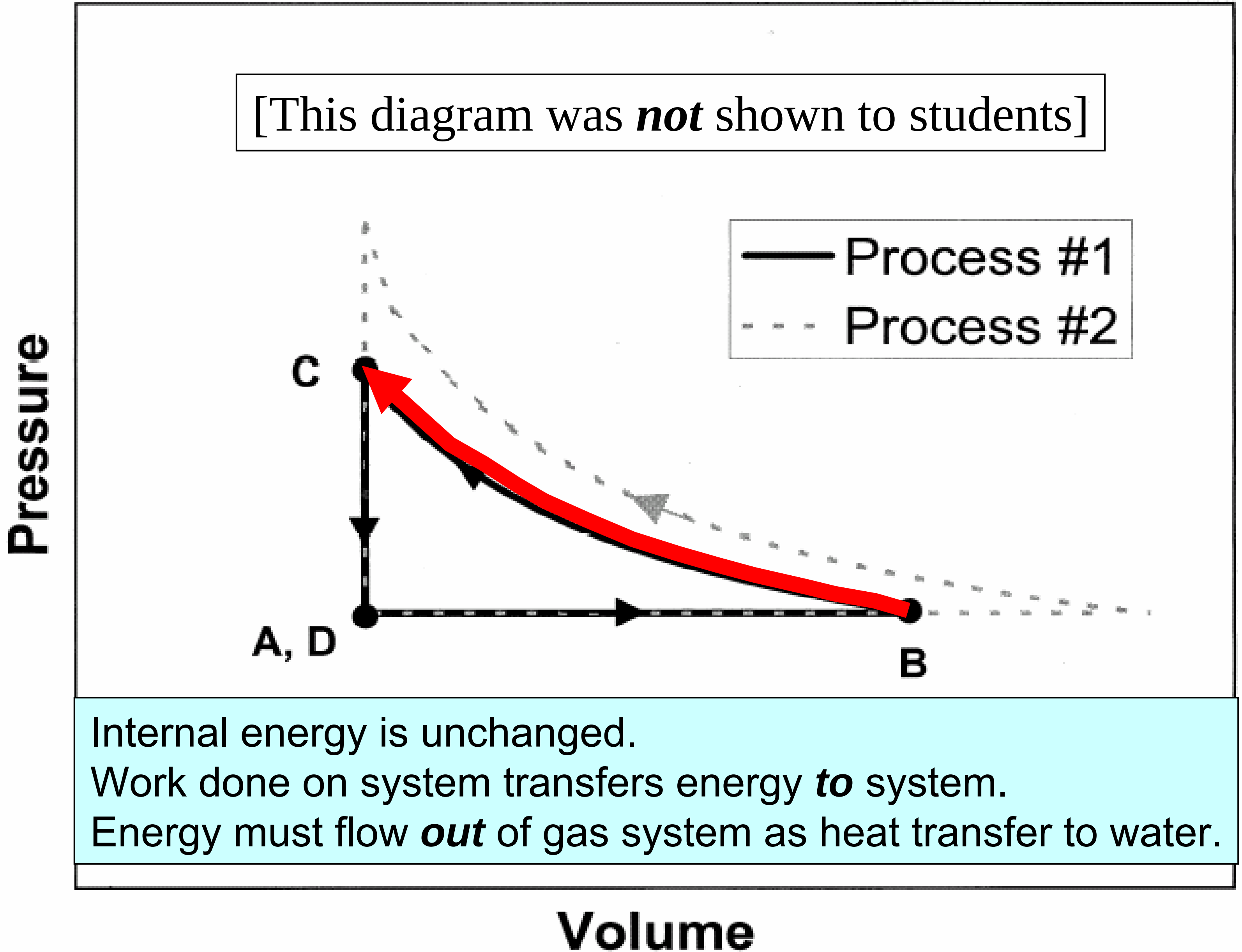
[This diagram was ***not*** shown to students]



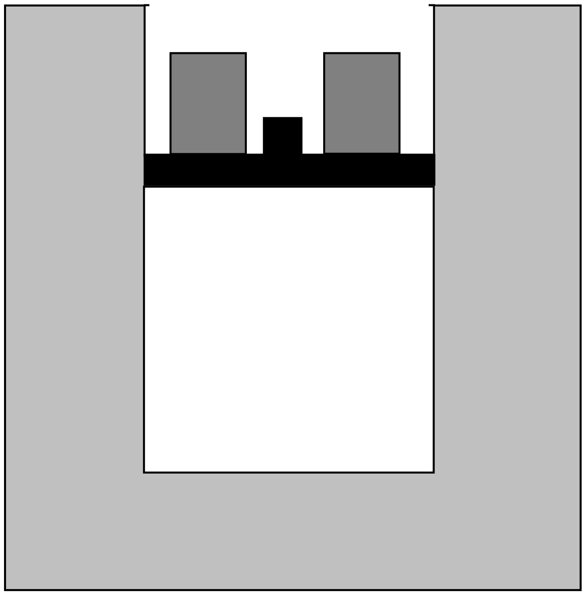
Internal energy is unchanged.


[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume
Internal energy is unchanged.
Work done on system transfers energy *to* system.

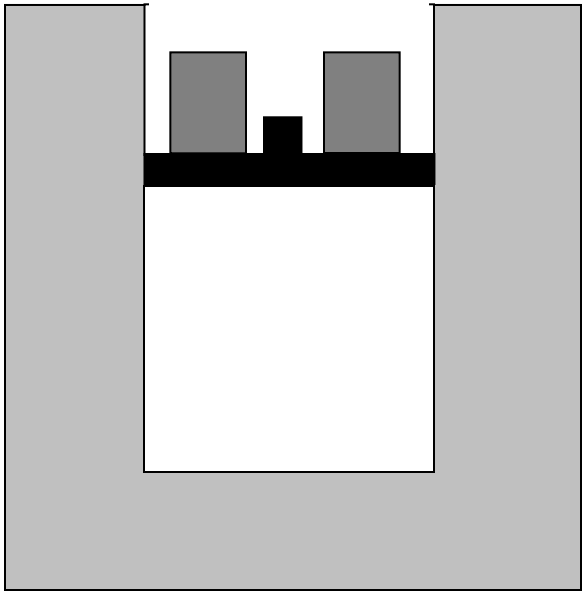
[This diagram was ***not*** shown to students]



Internal energy is unchanged.
Work done on system transfers energy ***to*** system.
Energy must flow ***out*** of gas system as heat transfer to water.



Question #4: During the process that occurs from time *B* to time *C*, is there *any* net energy flow between the gas and the water? If no, explain why not. If yes, is there a net flow of energy from gas to water, or from water to gas?



Question #4: During the process that occurs from time *B* to time *C*, is there *any* net energy flow between the gas and the water? If no, explain why not. If **yes**, is there a **net flow of energy from gas to water**, or from water to gas?

Results on Interview Question #4

No [$Q = 0$]	59%
Yes, from water to gas	3%
Yes, from gas to water	38%
With correct explanation	*31%*
With incorrect explanation	*6%*

Explanations for *Q* = 0

"*I would think if there was energy flow between the gas and the water, the temperature of the water would heat up*."

"*There is no energy flow because there is no change in temperature*."

"*Since the temperature stayed the same, there is no heat flow*."

Explanations for $Q = 0$

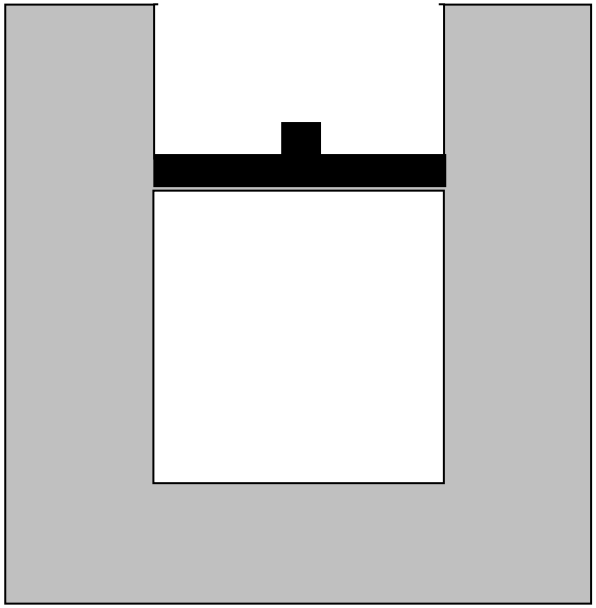
"*I would think if there was energy flow between the gas and the water, the temperature of the water would heat up*."

"*There is no energy flow because there is no change in temperature*."

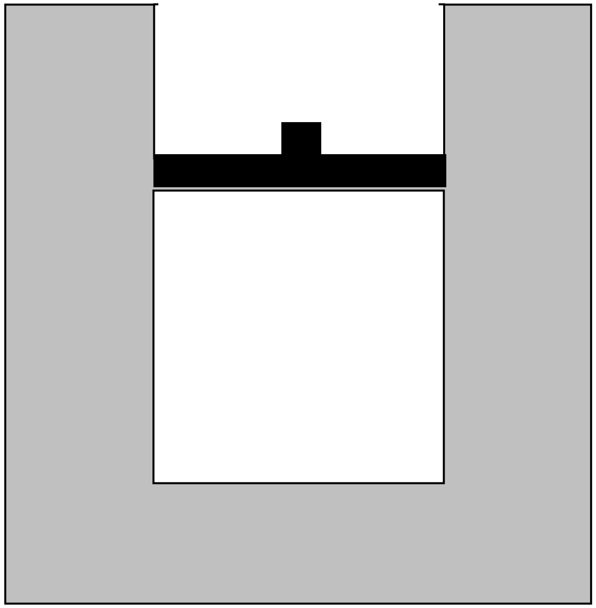
"*Since the temperature stayed the same, there is no heat flow*."

Widespread misunderstanding of "thermal reservoir" concept, in which heat may be transferred to or from an entity that has practically unchanging temperature

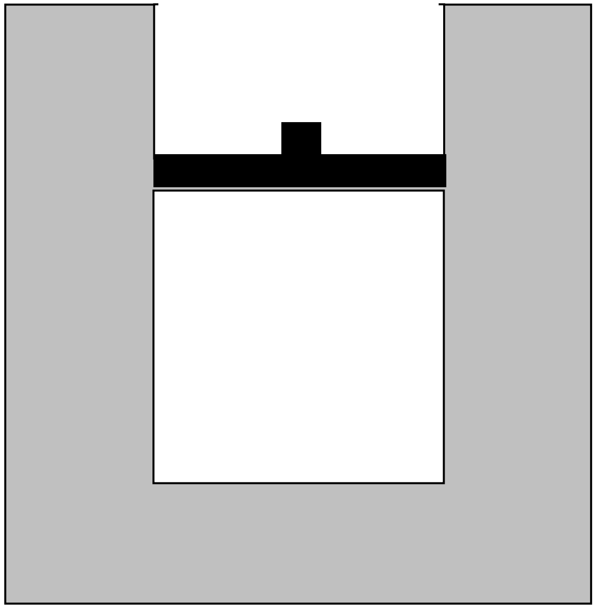
Now, the piston is locked into place so it *cannot move*, and the weights are removed from the piston.



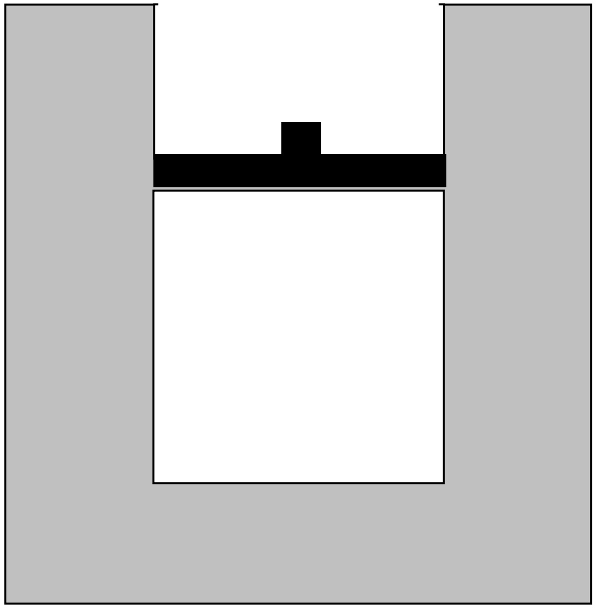
The system is left to sit in the room for many hours.

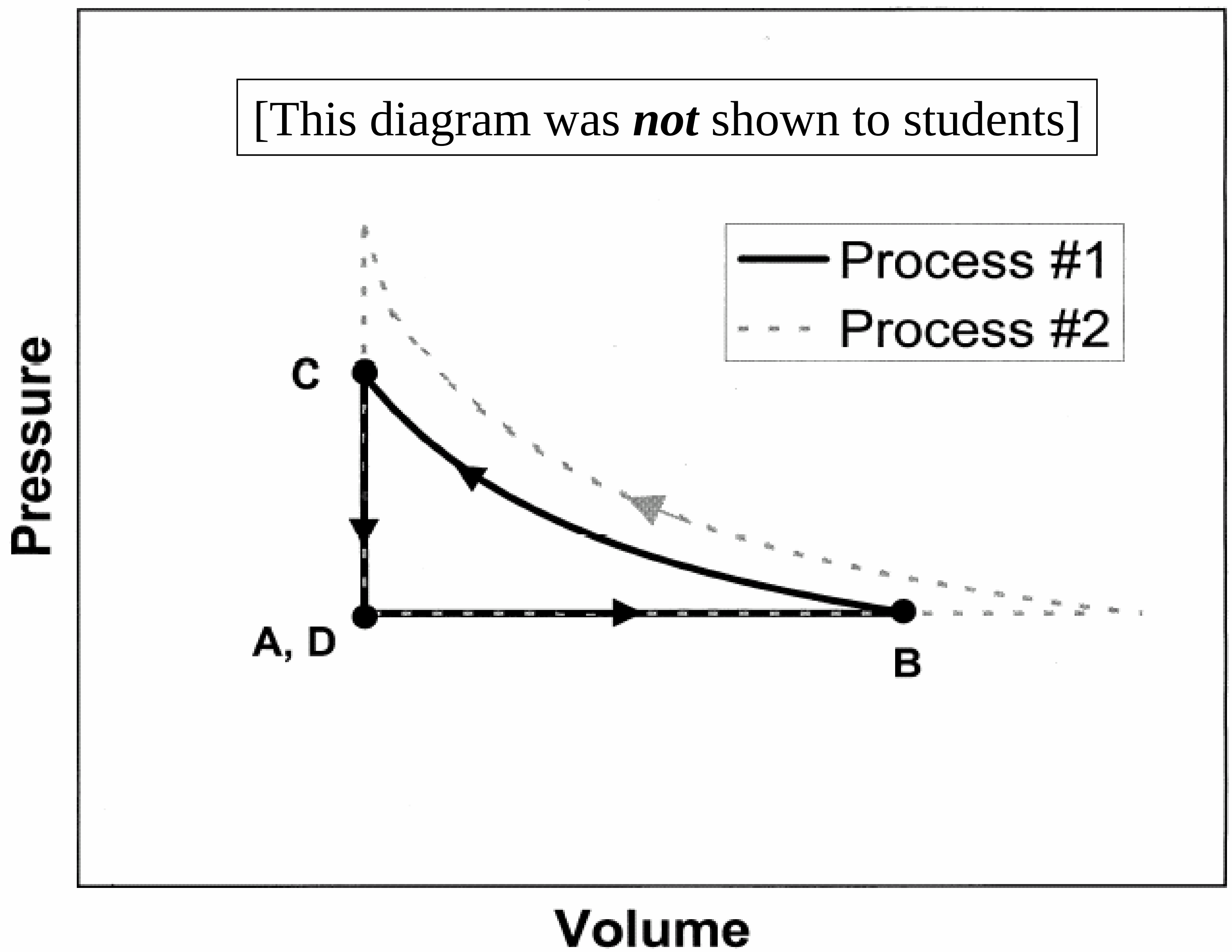


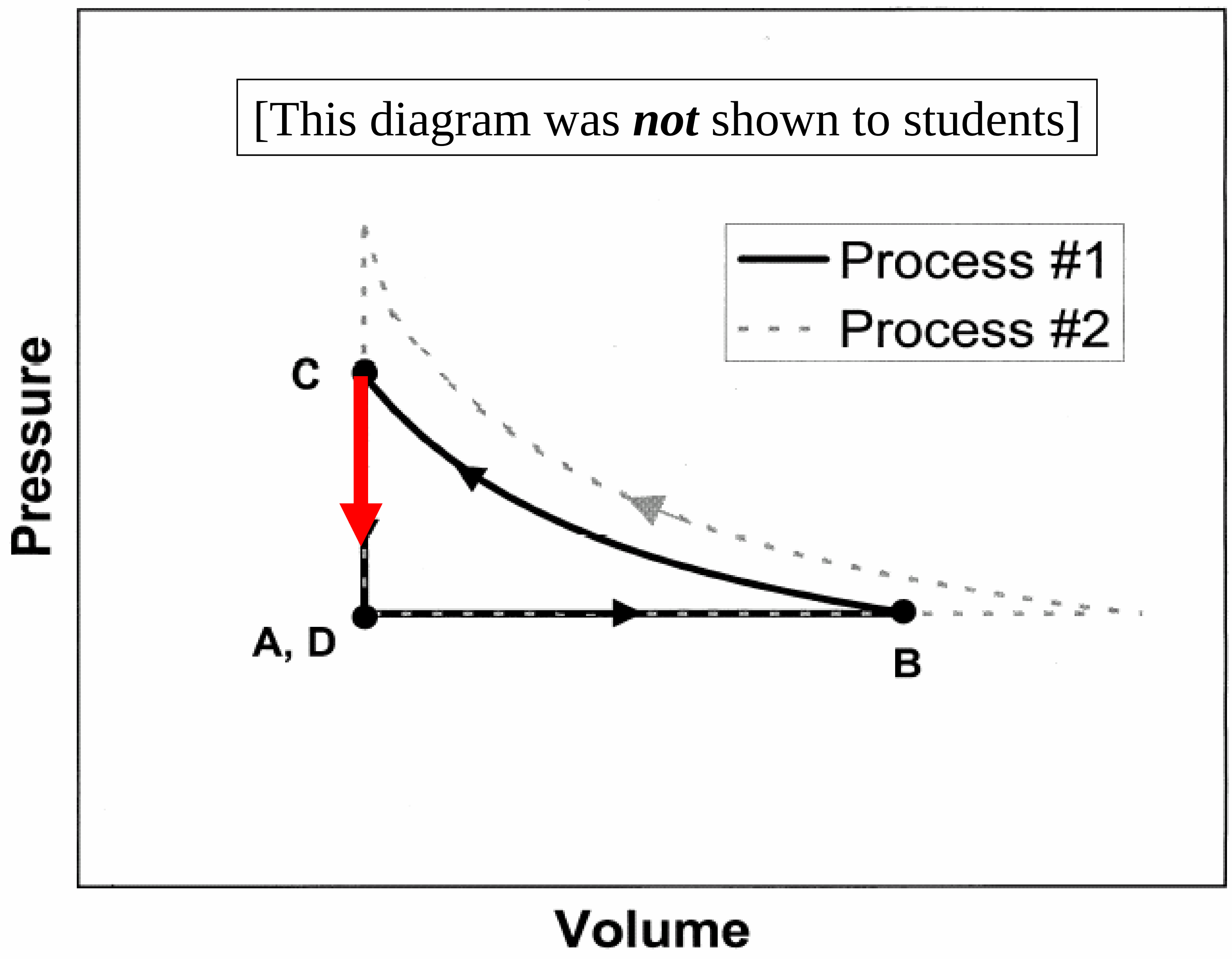
Eventually the entire system cools back down to the same room temperature it had at time ***A***.



After cooling is complete, it is time ***D.***




[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume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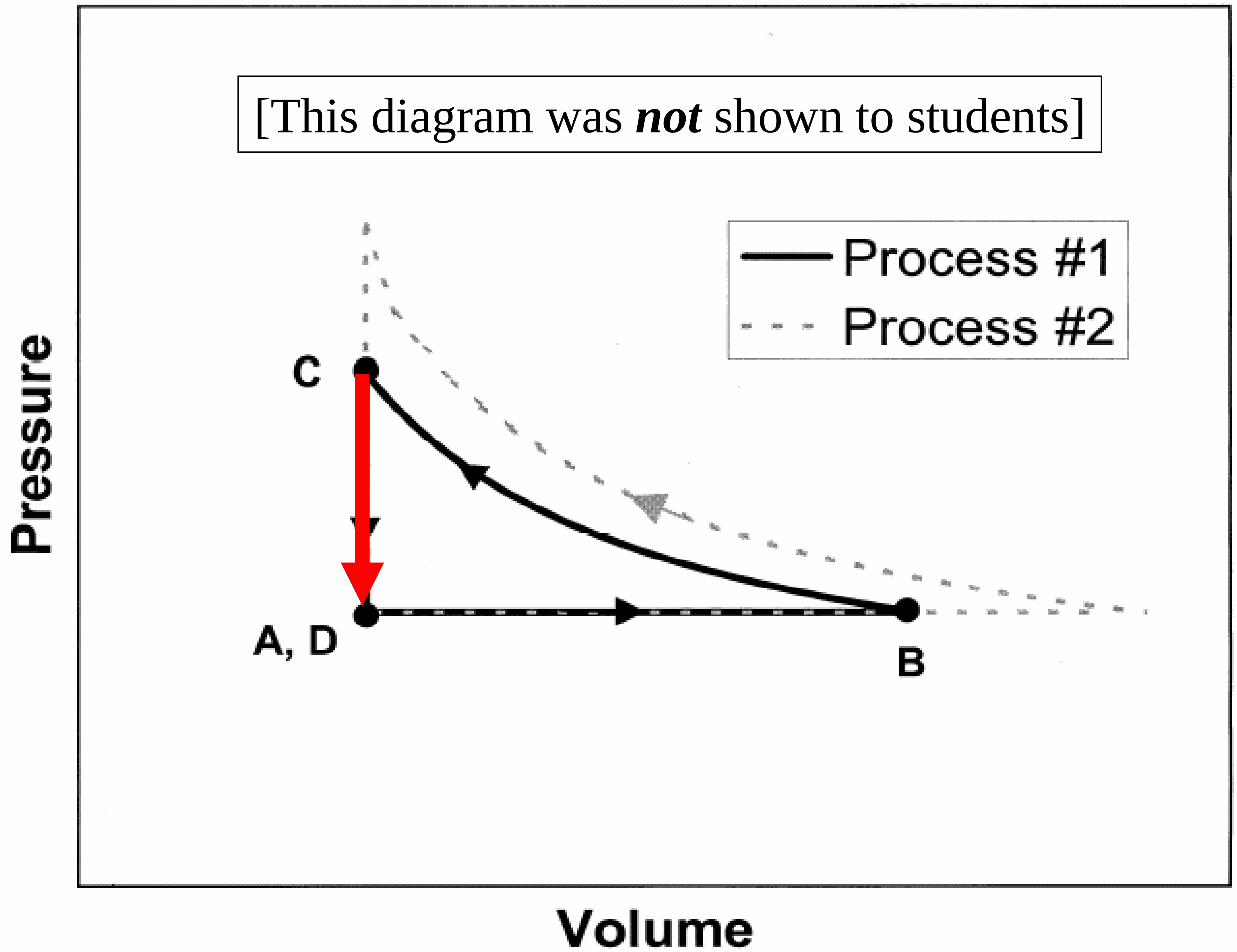
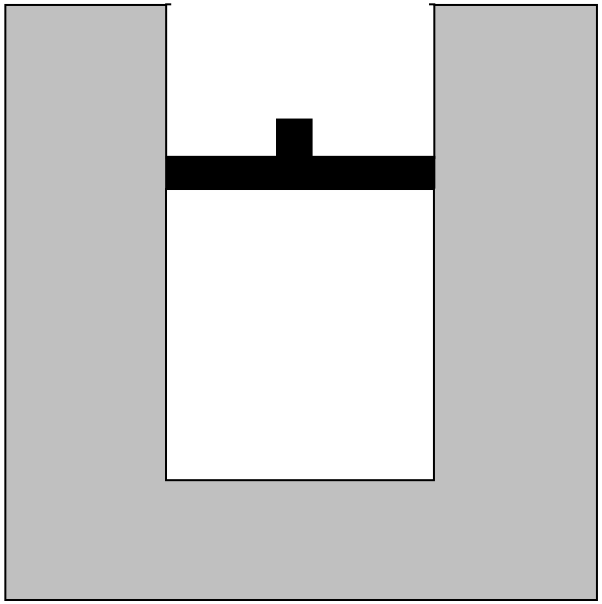
Process #1
Process #2
C
A, D
B
Pressure
Volume

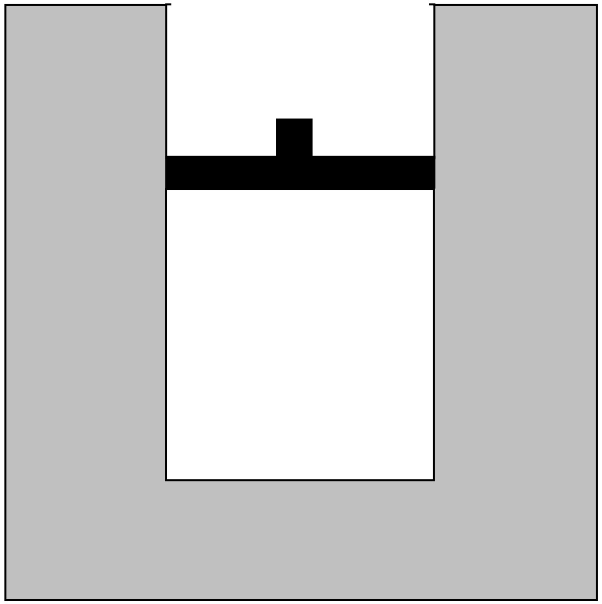

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



Question #6: Consider ***the entire process*** from time *A* to time *D*.

(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?



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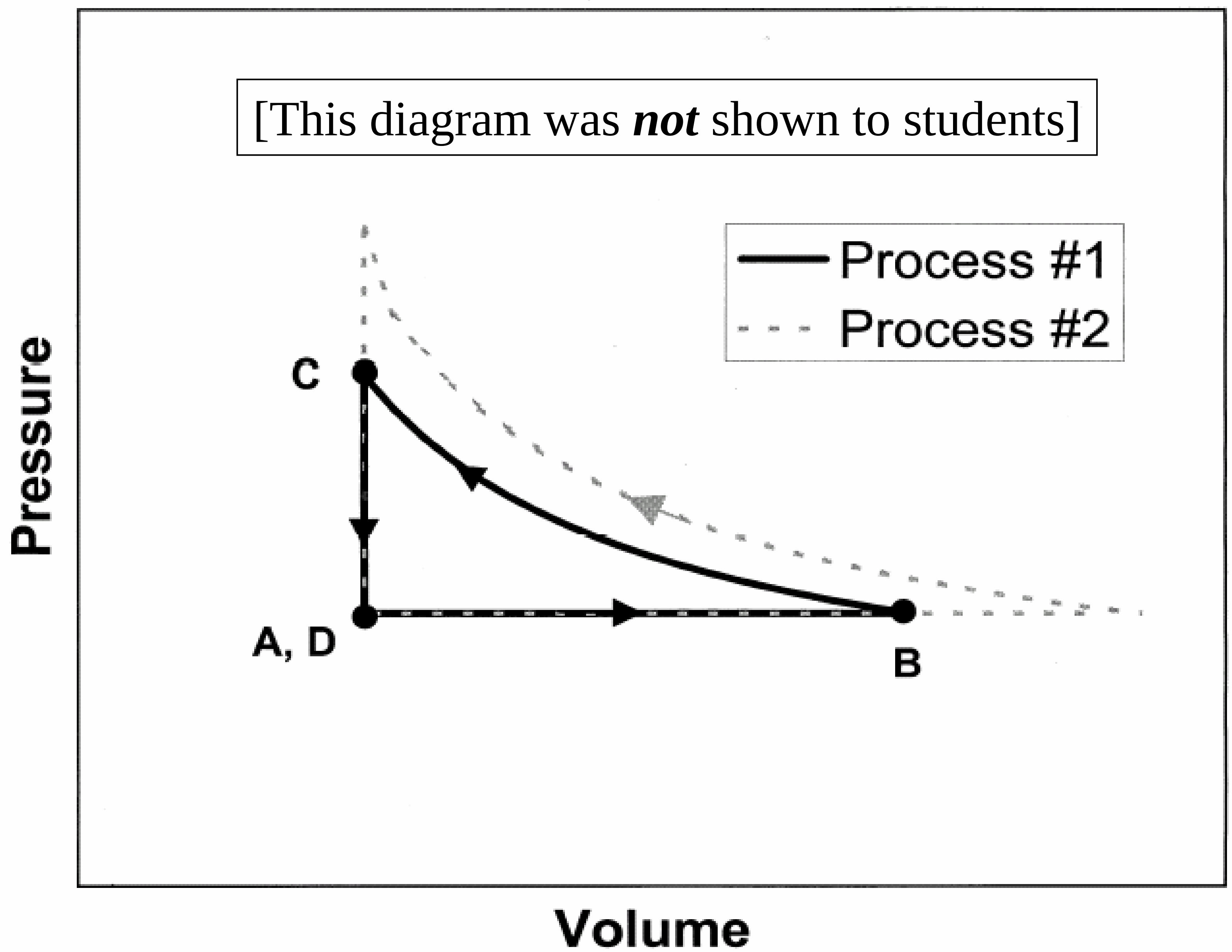
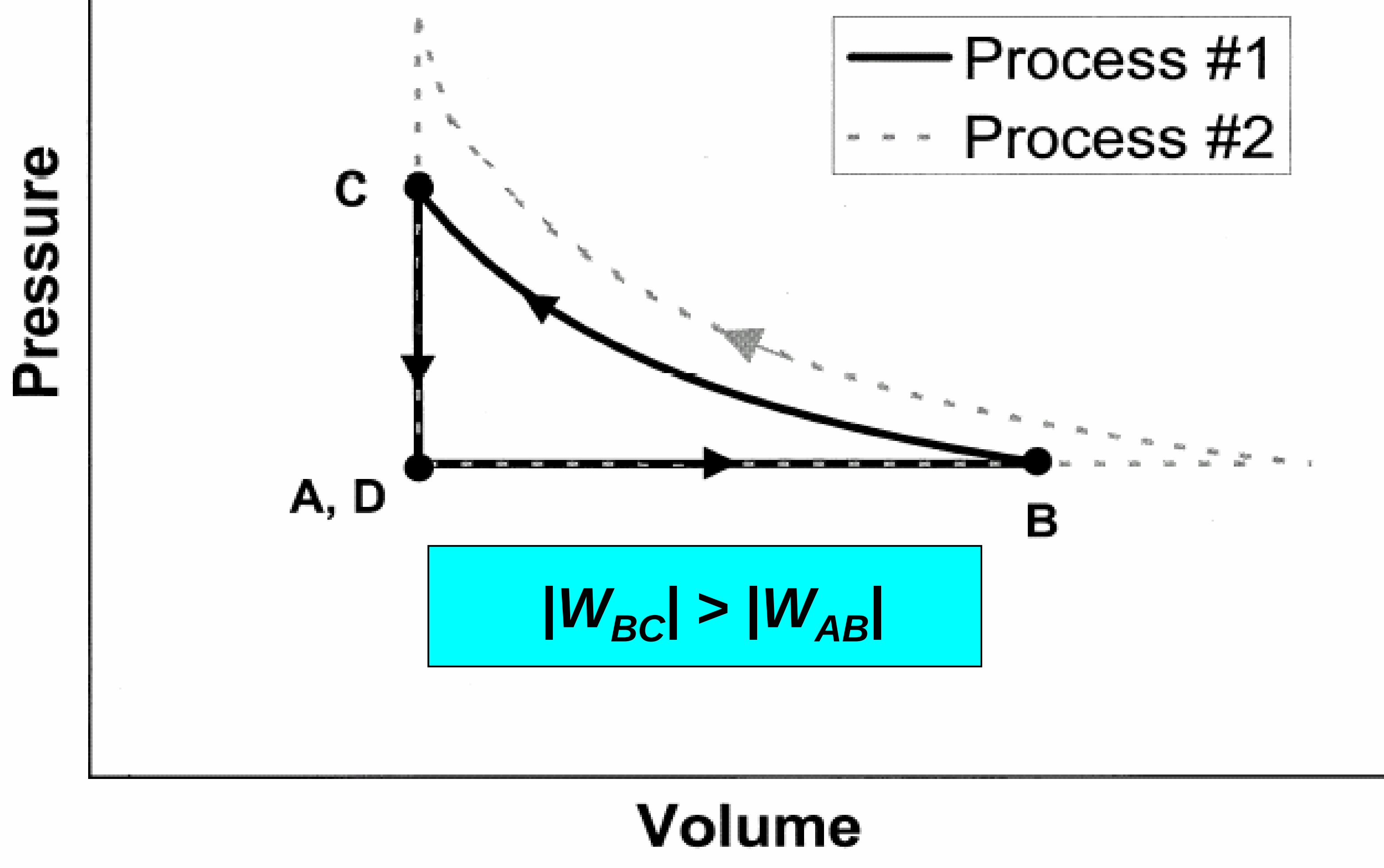
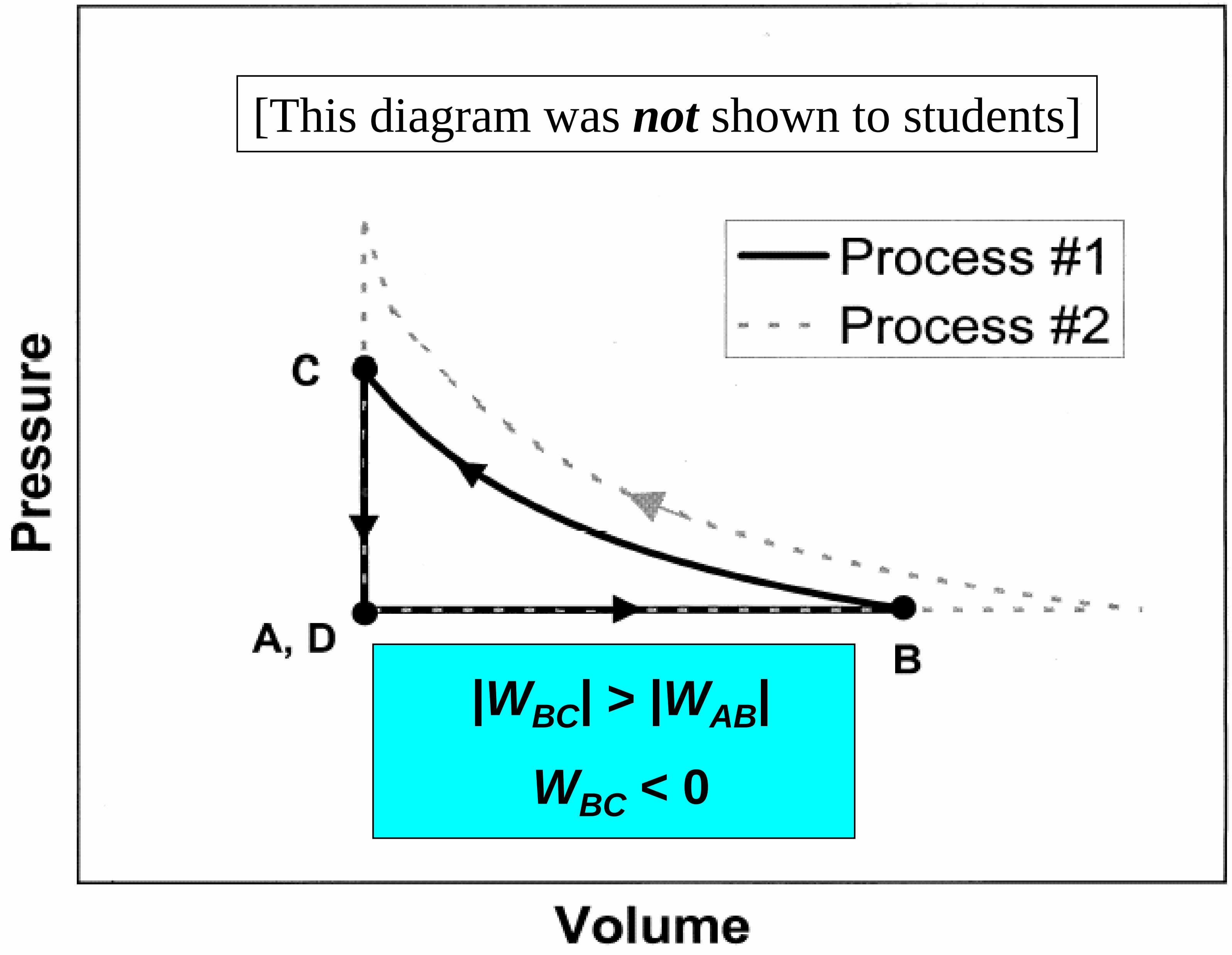


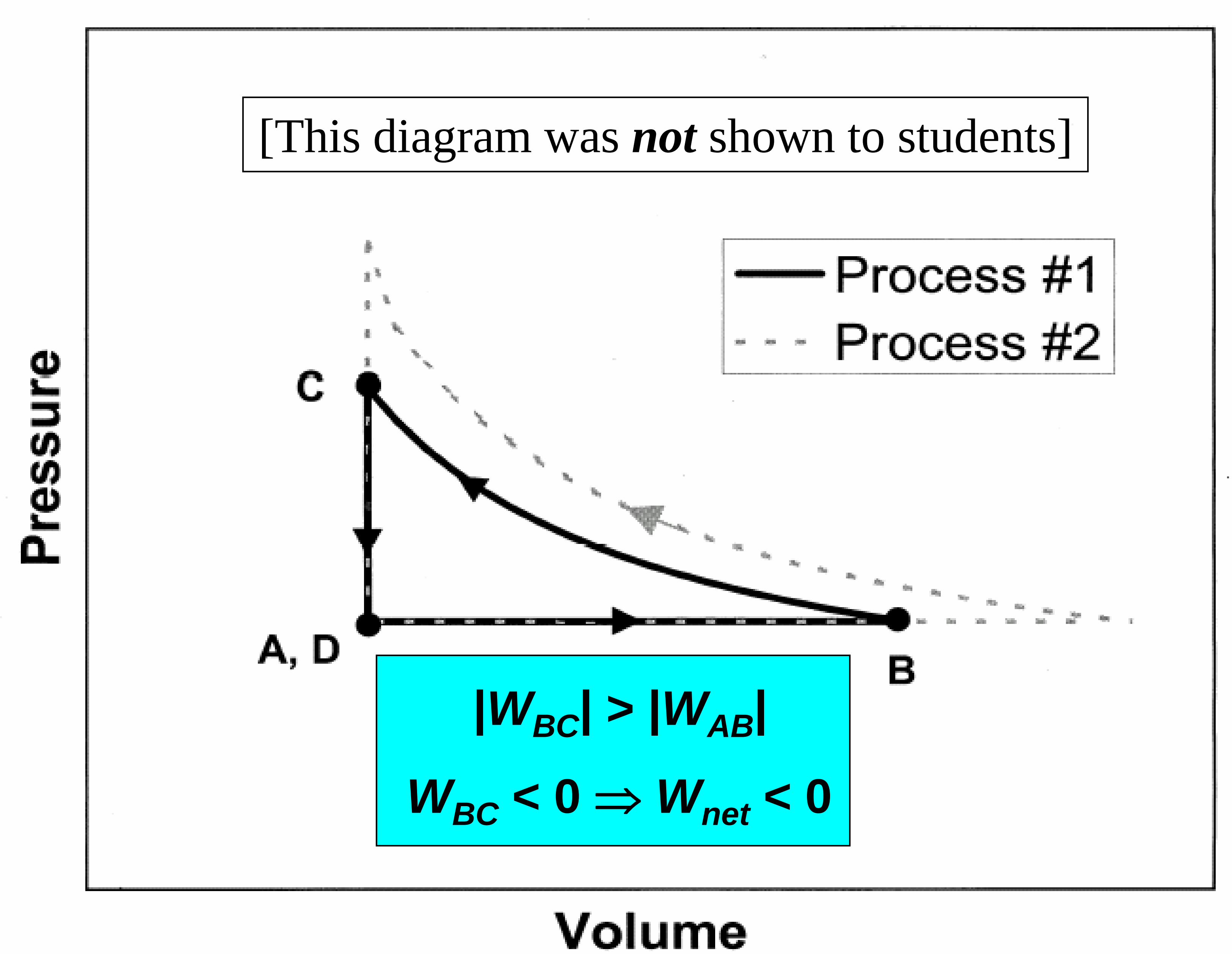
[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

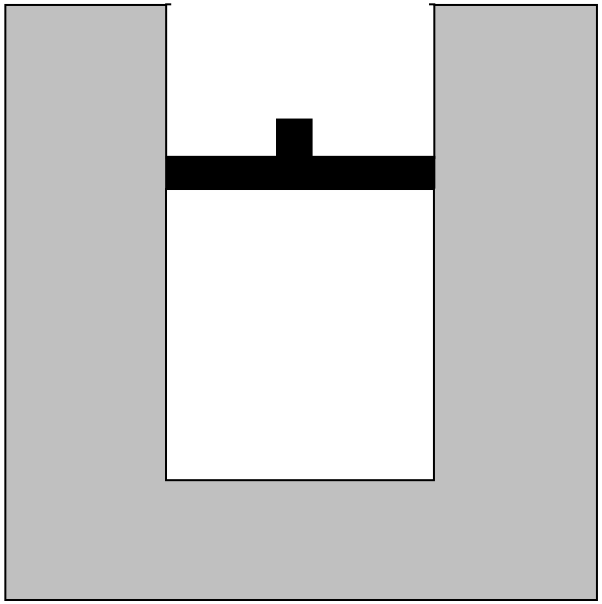
[This diagram was ***not*** shown to students]



$|W_{BC}| > |W_{AB}|$


[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
$|W_{BC}| > |W_{AB}|$
$W_{BC} < 0$
Pressure
Volume


[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume
$|W_{BC}| > |W_{AB}|$
$W_{BC} < 0 \Rightarrow W_{net} < 0$



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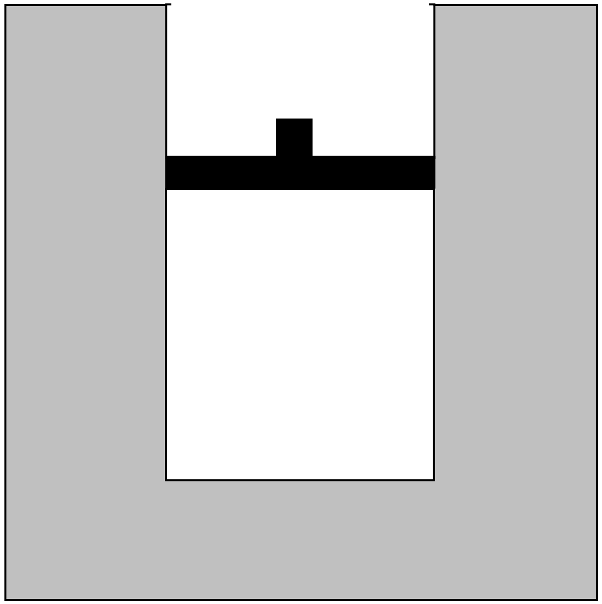

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(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or **(c) less than zero?**

(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

Results on Interview Question #6 (i)

$N = 32$

(a) $W_{net} > 0$: 16%

(b) $W_{net} = 0$: 63%

(c) $W_{net} < 0$: 19% *[correct]*

No response: 3%

Results on Interview Question #6 (i)

$N = 32$

(a) $W_{net} > 0$: 16%

(b) $W_{net} = 0$: 63%

(c) $W_{net} < 0$: 19%   *[correct]*

No response: 3%

Nearly two thirds of the interview sample believed that net work done was equal to zero.

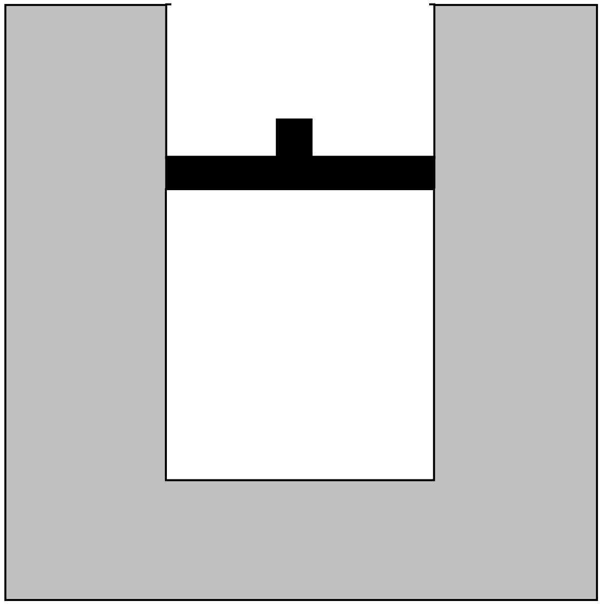
Explanations offered for $W_{net} = 0$

"[Student #1:] *The physics definition of work is like force times distance. And basically if you use the same force and you just travel around in a circle and come back to your original spot, technically you did zero work*."

Explanations offered for $W_{net} = 0$

"[Student #1:] *The physics definition of work is like force times distance. And basically if you use the same force and you just travel around in a circle and come back to your original spot, technically you did zero work*."

"[Student #2:] *At one point the volume increased and then the pressure increased, but it was returned back to that state . . . The piston went up so far and then it's returned back to its original position, retracing that exact same distance*."



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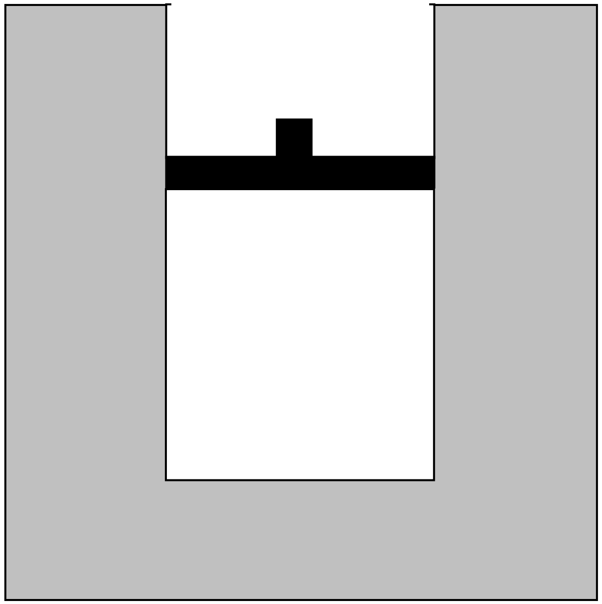

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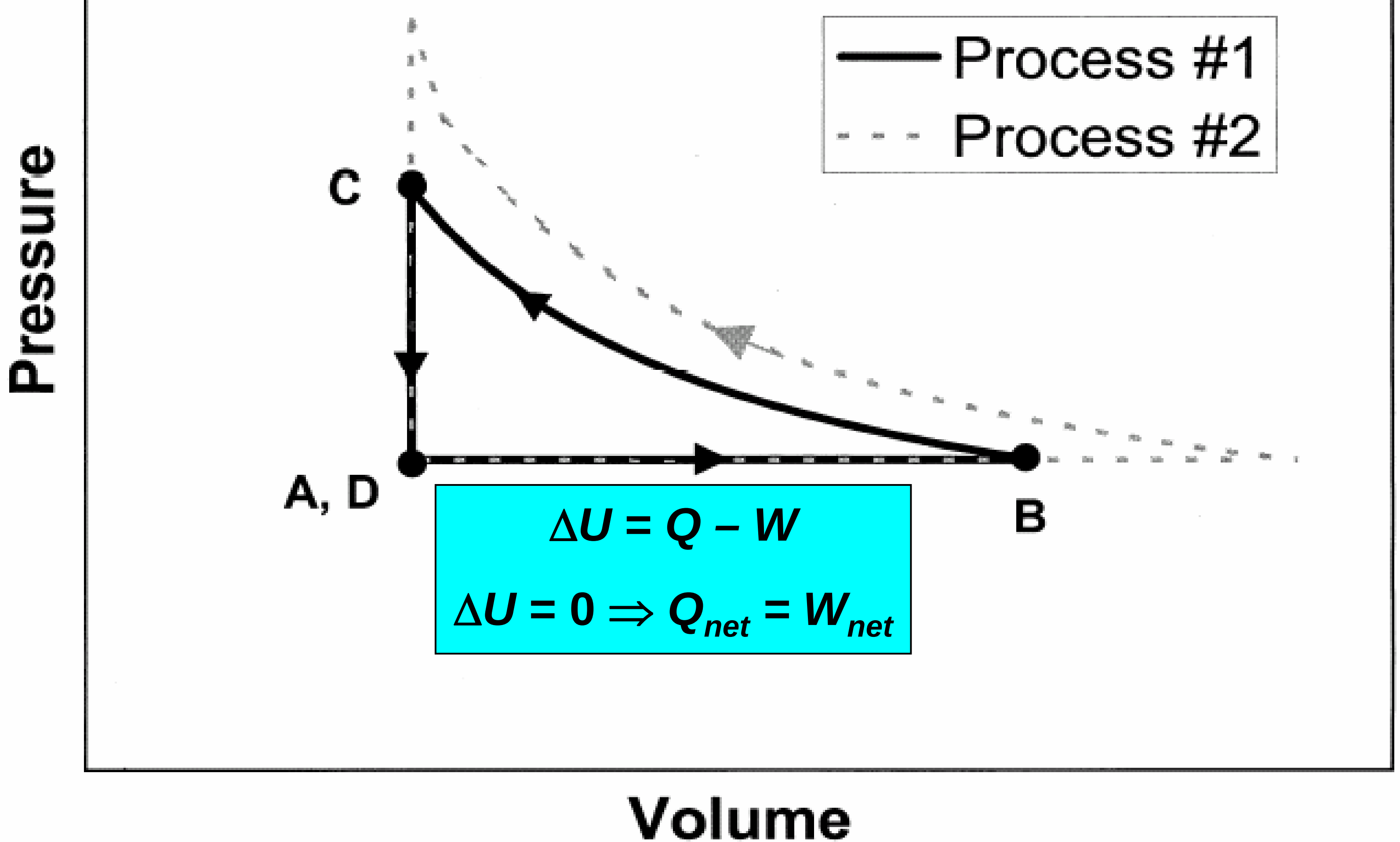
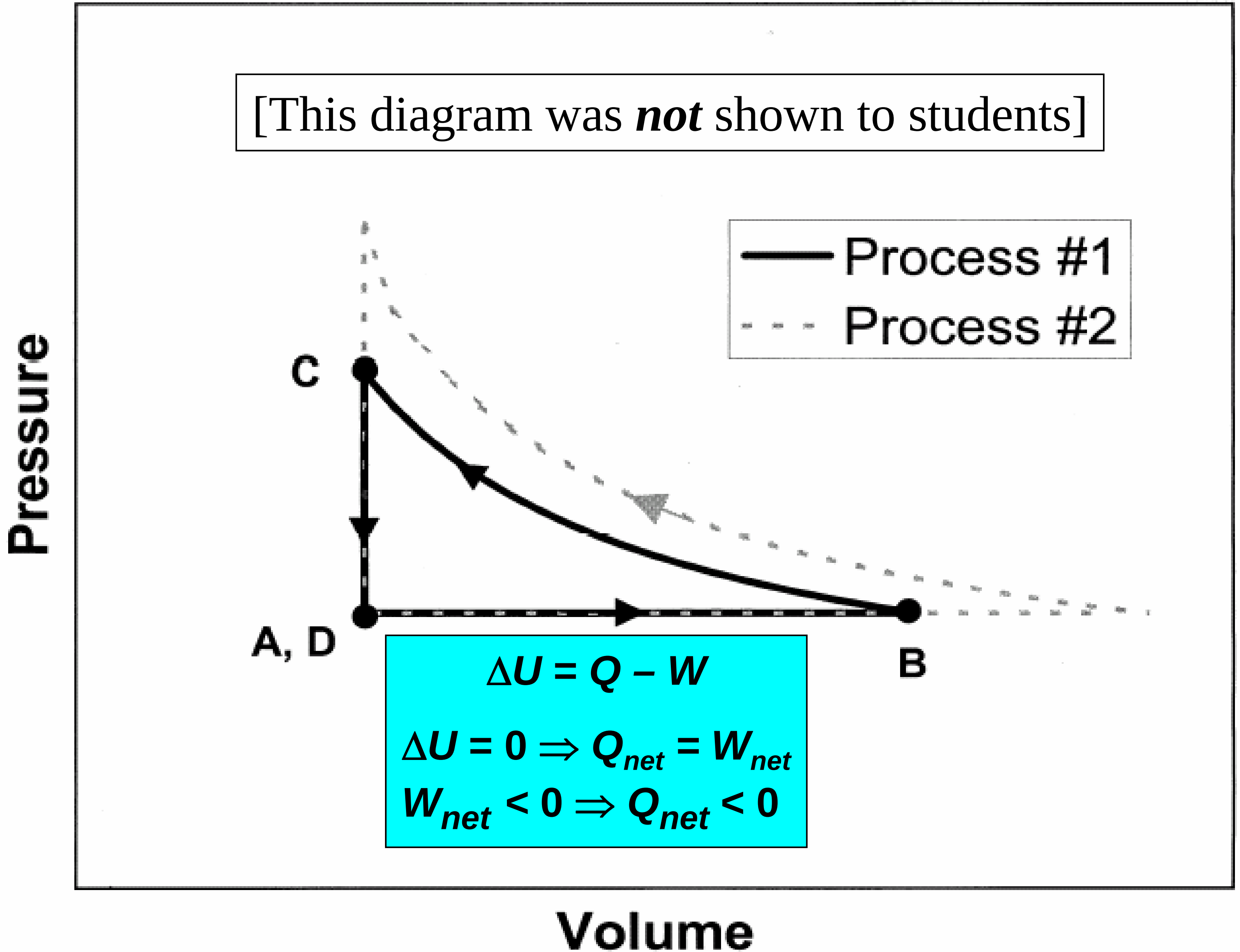
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

$$\Delta U = 0 \Rightarrow Q_{net} = W_{net}$$

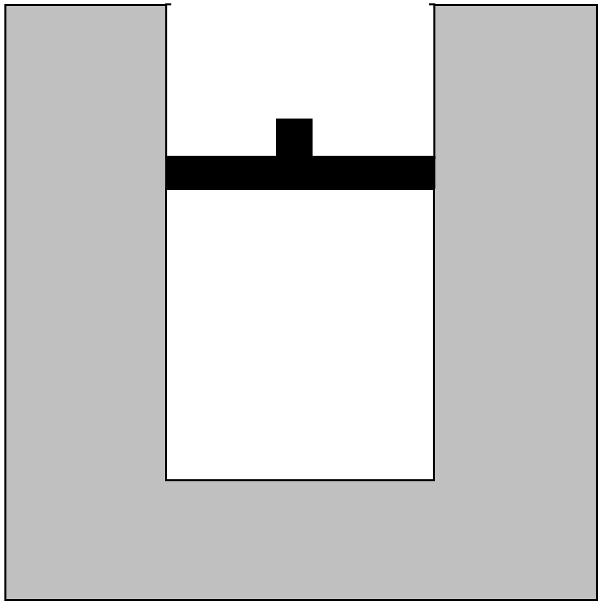
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

$$\Delta U = 0 \Rightarrow Q_{net} = W_{net}$$

$$W_{net} < 0 \Rightarrow Q_{net} < 0$$



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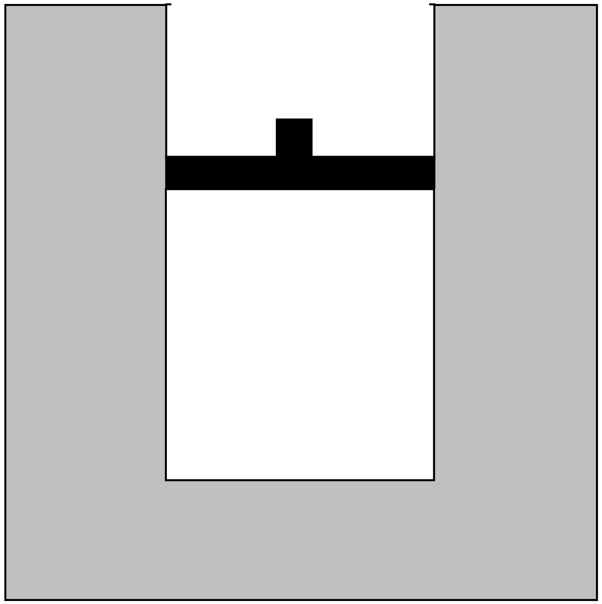


Question #6: Consider ***<u>the entire process</u>*** from time *A* to time *D*.

(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or **(c) less than zero?**

(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or **(c) less than zero?**

Results on Interview Question #6 (ii)

$N = 32$

(a) $Q_{net} > 0$ **9%**

(b) $Q_{net} = 0$ **69%**

(c) $Q_{net} < 0$ **16%** ***[correct]***

with correct explanation: 13%

with incorrect explanation: 3%

Uncertain: 6%

Results on Interview Question #6 (ii)

$N = 32$

(a) $Q_{net} > 0$ **9%**

(b) $Q_{net} = 0$ **69%**

(c) $Q_{net} < 0$ **16%** ***[correct]***

with correct explanation: ***13%***

with incorrect explanation: ***3%***

Uncertain: **6%**

More than two thirds of the interview sample believed that net heat absorbed was equal to zero.

Explanation offered for $Q_{net} = 0$

"*The heat transferred to the gas . . . is equal to zero . . . . The gas was heated up, but it still returned to its equilibrium temperature. So whatever energy was added to it was distributed back to the room.*"

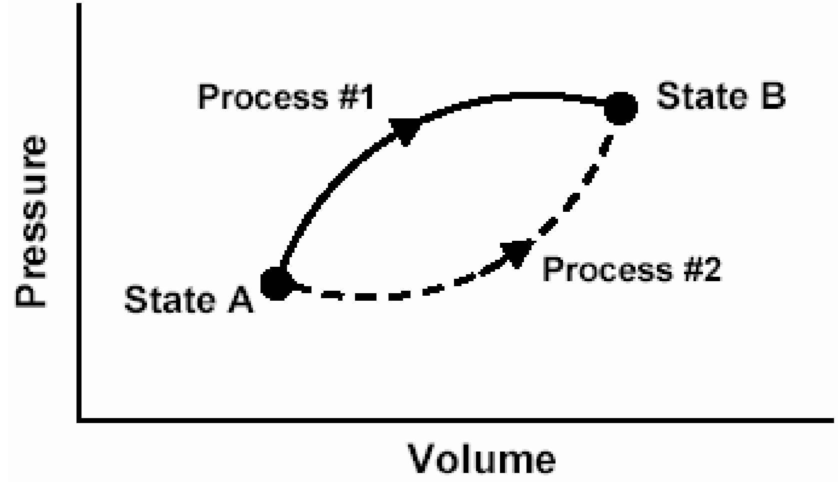
Most students thought that both Q_{net} and W_{net} are equal to zero

- 56% believed that both the net work done ***and*** the total heat transferred would be zero.
- Only three out of 32 students (9%) answered both parts of Interview Question #6 correctly.

Predominant Themes of Students' Reasoning

1. Understanding of concept of state function in the context of energy.
2. Belief that work is a state function.
3. Belief that heat is a state function.
4. Belief that net work done and net heat transferred during a cyclic process are zero.
5. Inability to apply the first law of thermodynamics.

This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:



[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

1. Is *W* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2? Explain.

2. Is *Q* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2?

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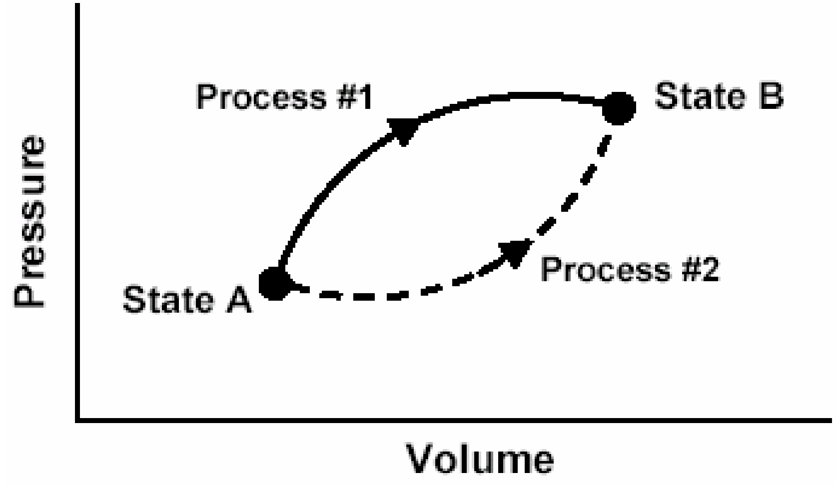
Change in internal energy is the same for Process #1 and Process #2.



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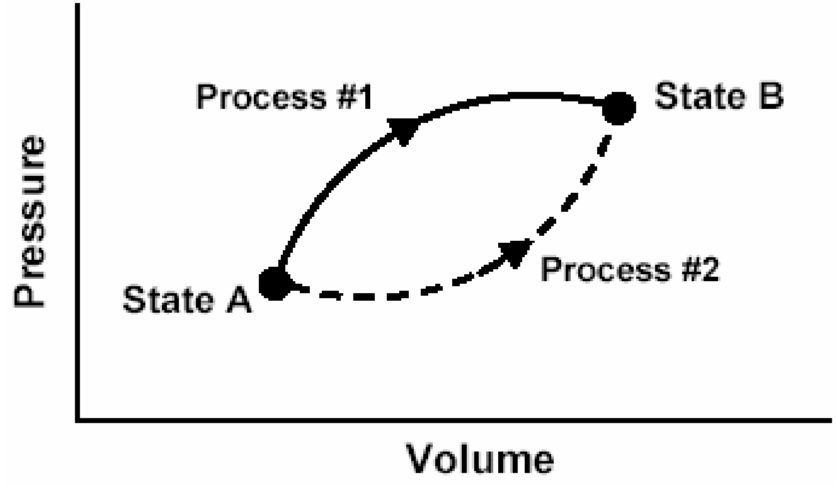
$Q_1 > Q_2$



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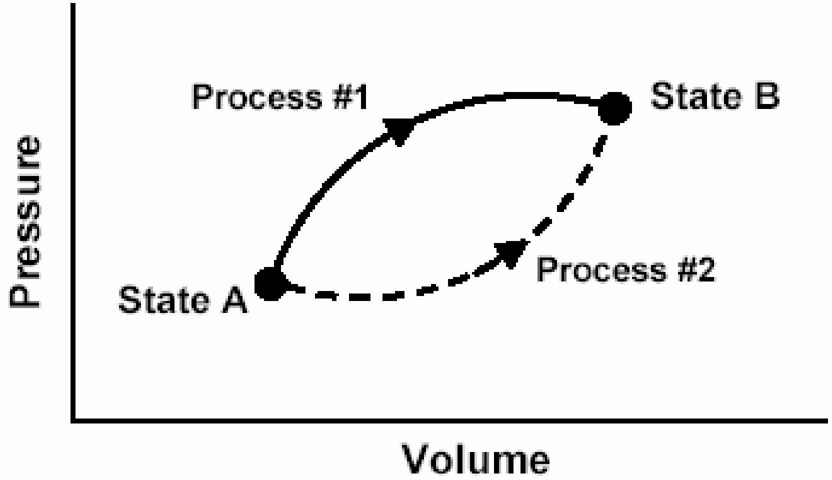

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(Heat question)

	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
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Examples of "Acceptable" Student Explanations for $Q_1 > Q_2$

"$\Delta U = Q - W$. *For the same* ΔU, *the system with more work done must have more* Q *input so process #1 is greater*."

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"Q *is greater for process one because it does more work; the energy to do this work comes from the* Q_{in}."

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Correct or partially correct explanation	**14%**	**10%**	**10%**	**19%**
Incorrect, or missing explanation	**42%**	**30%**	**30%**	**15%**

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Consistent with results of Loverude, Kautz, and Heron, Am. J. Phys. (2002), for Univ. Washington, Univ. Maryland, and Univ. Illinois

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Students very often attribute state-function properties to process-dependent quantities.

Primary Findings

*Even **after** instruction, many students (40-80%):*

- believe that heat and/or work are state functions independent of process

- believe that net work done and net heat absorbed by a system undergoing a cyclic process must be zero

- are unable to apply the First Law of Thermodynamics in problem solving

Some Strategies for Instruction

- Loverude et al.: Solidify students' concept of work in mechanics context (e.g., positive and negative work);
- Develop and emphasize concept of work as an energy-transfer mechanism in thermodynamics context.

Some Strategies for Instruction

- Try to build on students' understanding of state-function concept in context of energy;
- Focus on meaning of heat as ***transfer*** of energy, ***not*** quantity of energy residing in a system;
- Emphasize contrast between heat and work as energy-transfer mechanisms.

Some Strategies for Instruction

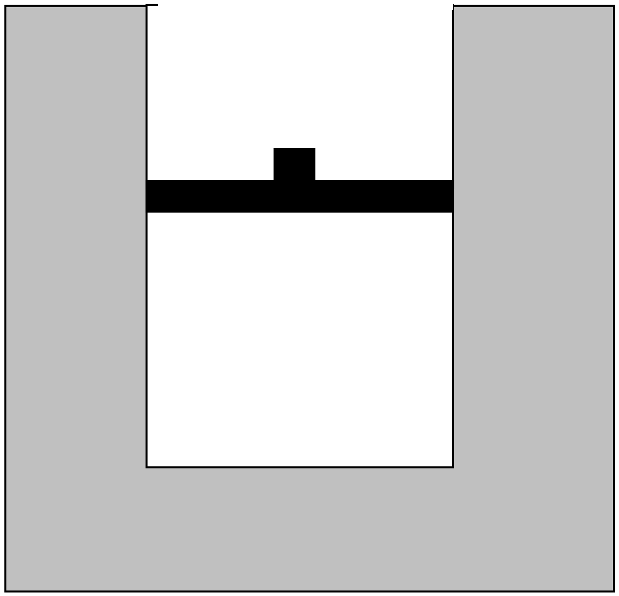
- Guide students to make increased use of *PV*-diagrams and similar representations.
- Practice converting between a diagrammatic representation and a physical description of a given process, especially in the context of cyclic processes.

Some Strategies for Instruction

- Certain common idealizations are very troublesome for many students (e.g., the relation between temperature and kinetic energy of an ideal gas; the meaning of thermal reservoir).
- The persistence of these difficulties suggests that it might be useful to guide students to provide their own justifications for commonly used idealizations.

Cyclic Process Worksheet

(adapted from interview questions)

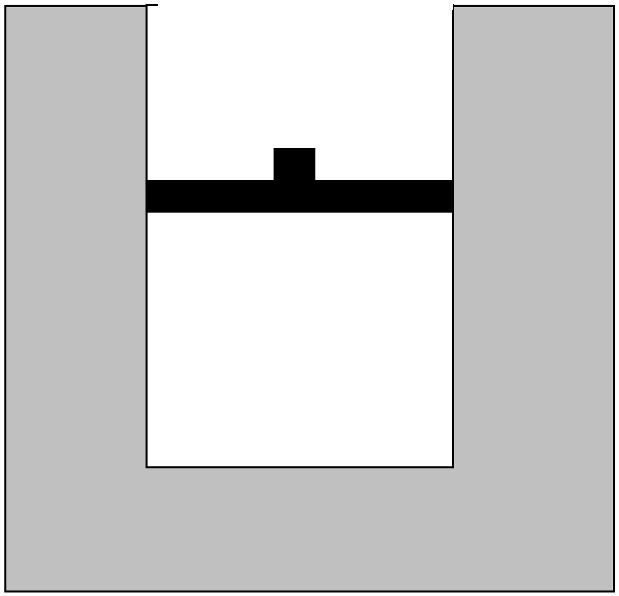


Worksheet Strategy

- First, allow students to read description of entire process and answer questions regarding work and heat.

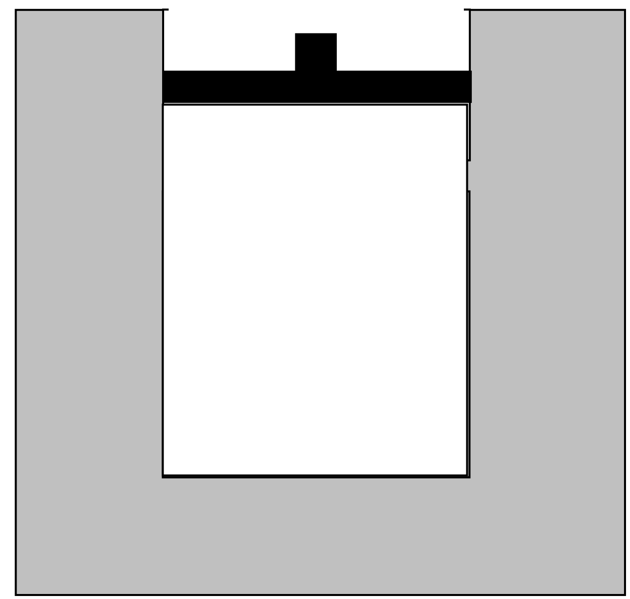
Time *A*

System heated



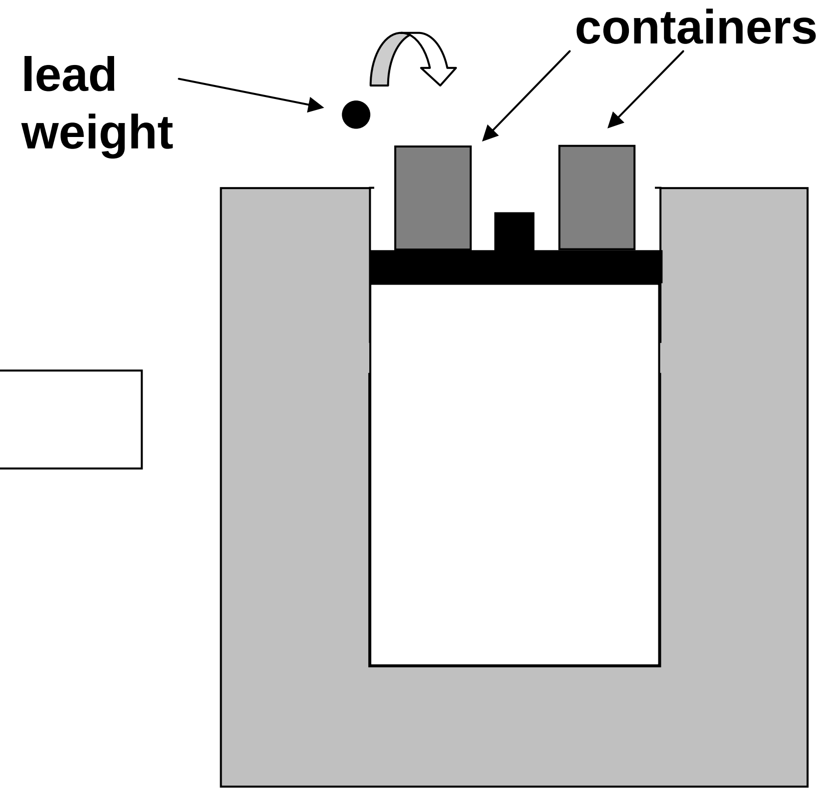
Time *B*

System heated, piston goes up.



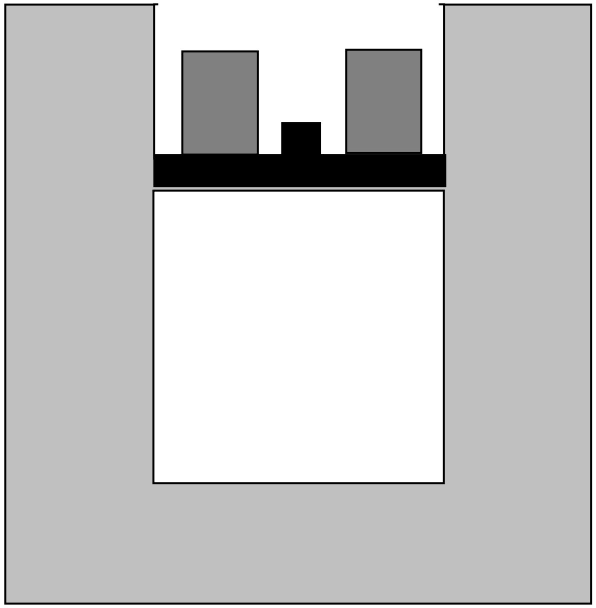
Time *B*

Weights added



Time *C*

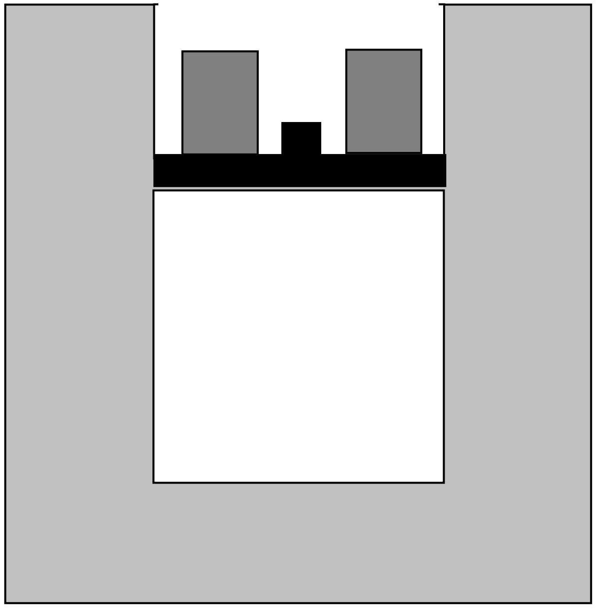
Weights added, piston goes down.



Time *C*

Weights added, piston goes down.

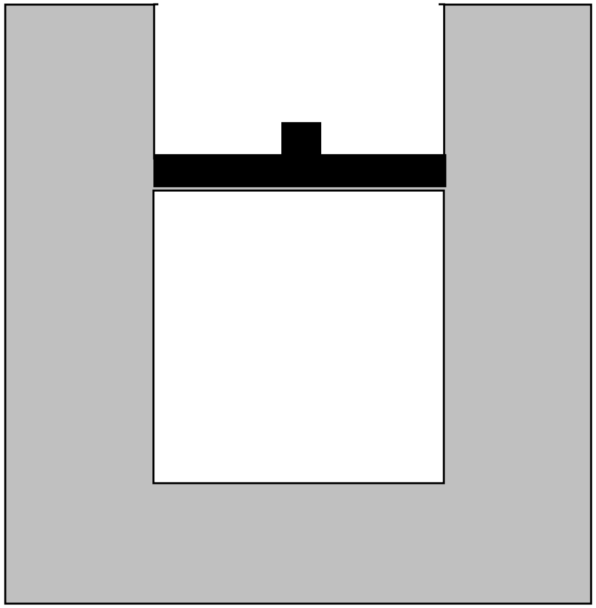
[Temperature remains constant]



Time *C*

Temperature *C*

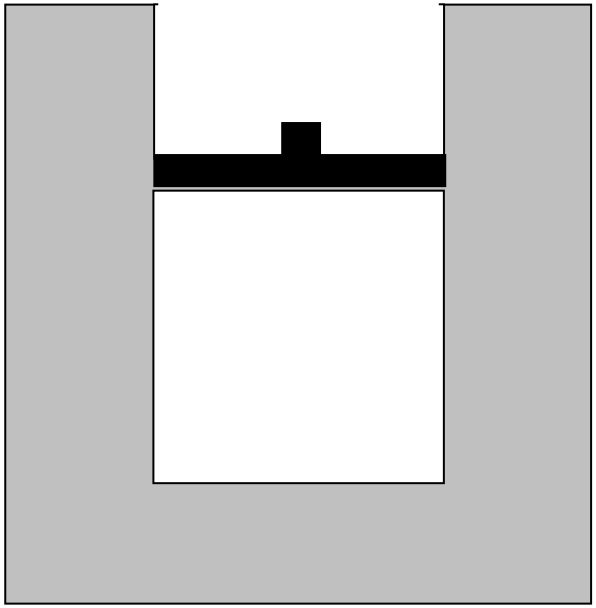
Piston locked

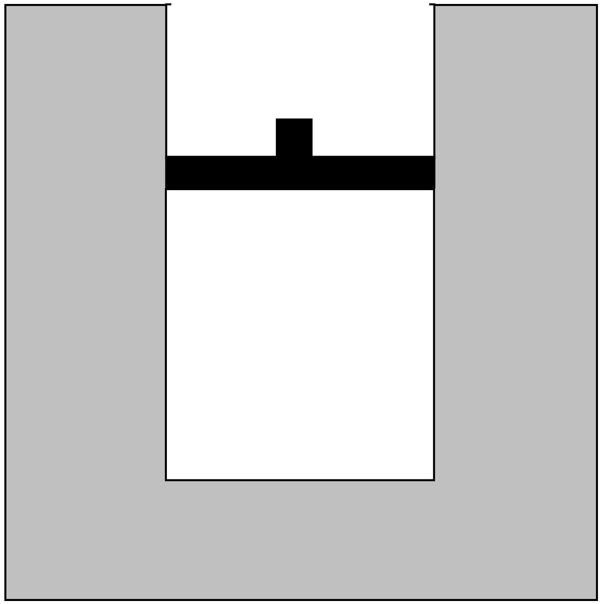


Time *D*

Temperature *D*

Piston locked, temperature goes down.

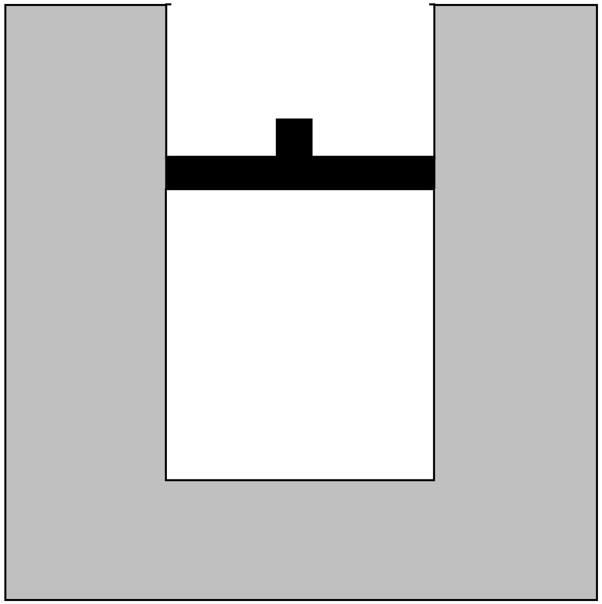




Question #6: Consider ***<u>the entire process</u>*** from time *A* to time *D*.

(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?



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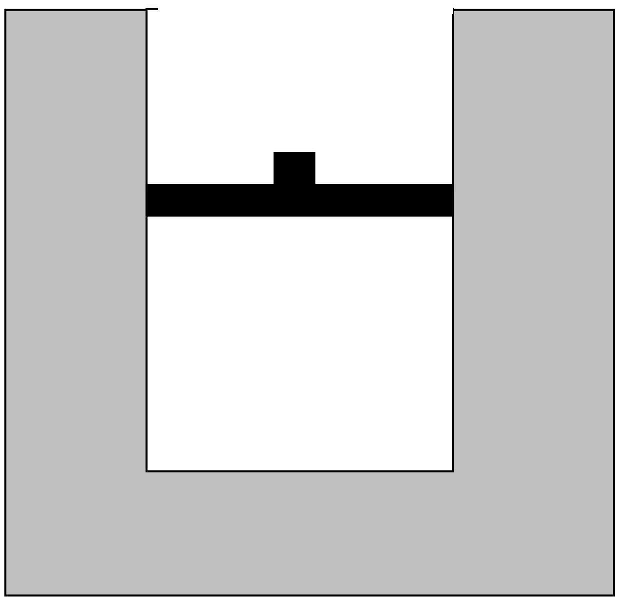
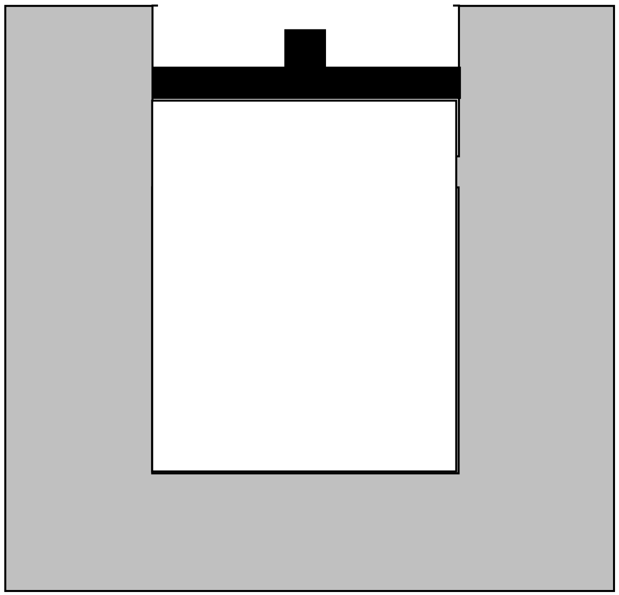
Worksheet Strategy

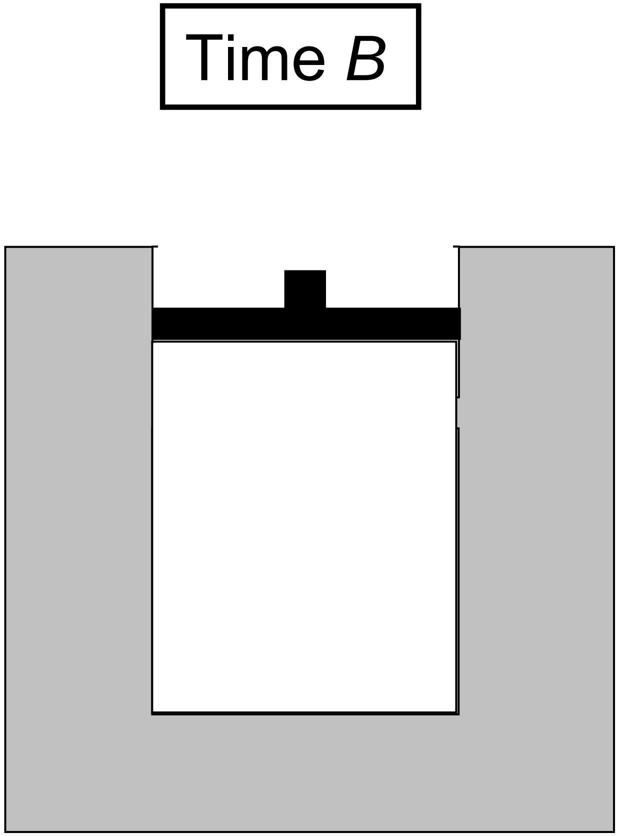
- First, allow students to read description of entire process and answer questions regarding work and heat.
- Then, prompt students for step-by-step responses.

Time *A*



Time *B*

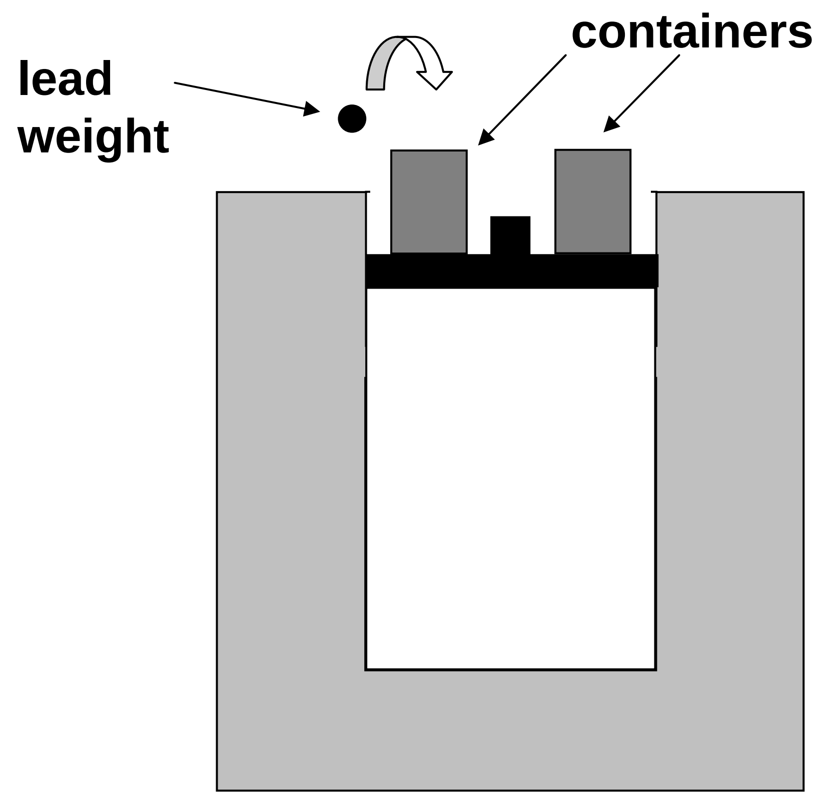




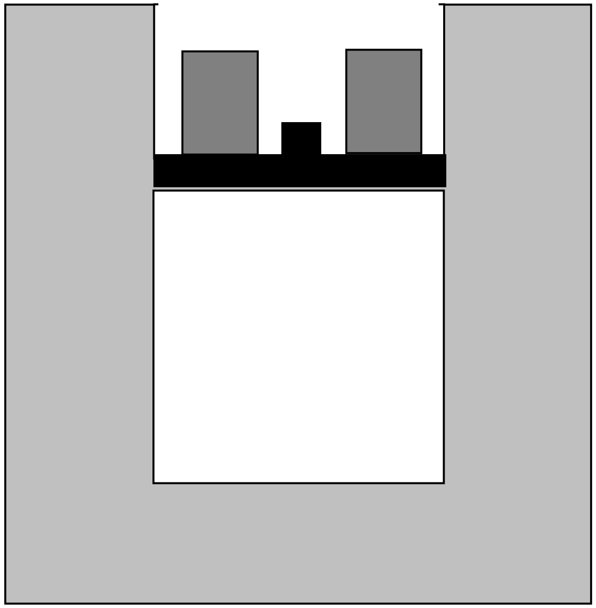
1) For the process A → B, is the work done by the system (W_{AB}) *positive*, *negative*, or *zero*?

Explain your answer.

Time *B*

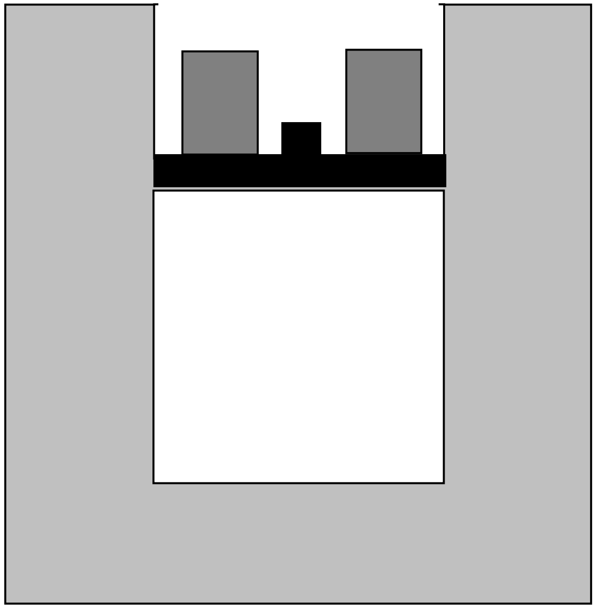


Time *C*



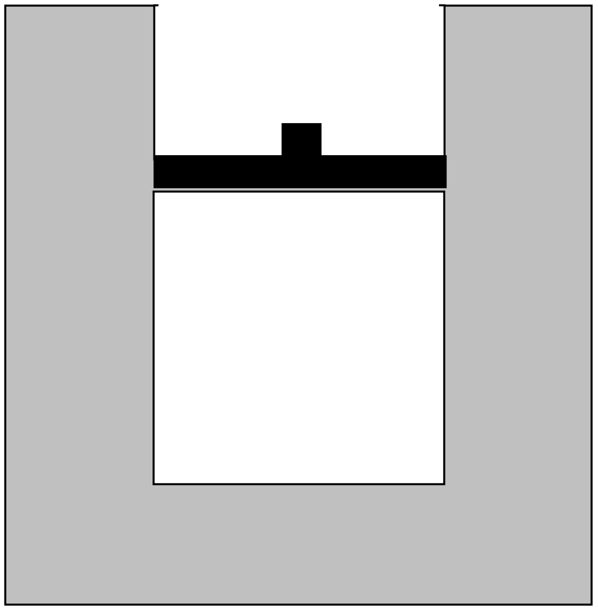
Time *C*

2) For the process B → C, is the work done by the system (W_{BC}) *positive*, *negative*, or *zero*?

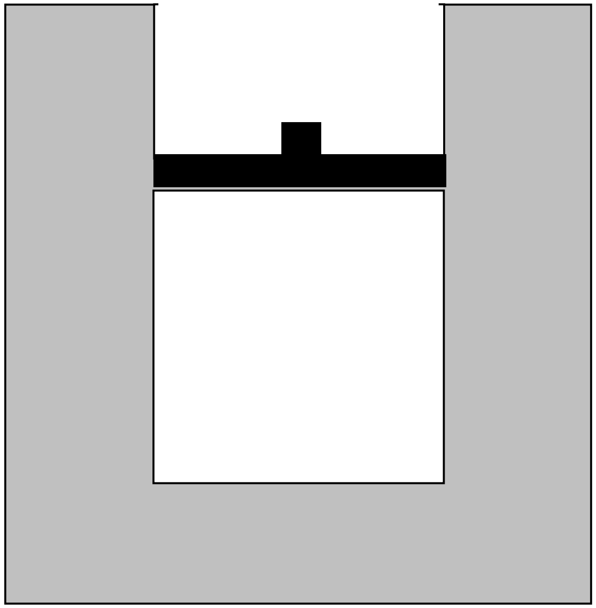


Time *C*

Temperature *C*



Time *D*



Temperature *D*

3) For the process C → D, is the work done by the system (W_{CD}) *positive*, *negative*, or *zero*?

1) For the process A → B, is the work done by the system (W_{AB}) *positive*, *negative*, or *zero*?

2) For the process B → C, is the work done by the system (W_{BC}) *positive*, *negative*, or *zero*?

3) For the process C → D, is the work done by the system (W_{CD}) *positive*, *negative*, or *zero*?

4) Rank the *absolute values* $|W_{AB}|$, $|W_{BC}|$, and $|W_{CD}|$ from largest to smallest; if two or more are equal, use the "=" sign:

largest ________________________________ *smallest*

Explain your reasoning.

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largest $|W_{BC}| > |W_{AB}| > |W_{CD}| = 0$ *smallest*

Explain your reasoning.

Worksheet Strategy

- First, allow students to read description of entire process and answer questions regarding work and heat.
- Then, prompt students for step-by-step responses.
- Finally, compare results of the two chains of reasoning.

Consider the net work done by the system during the complete process A → D, where

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i) Is this quantity *greater than zero*, *equal to zero*, or *less than zero*?

ii) Is your answer consistent with the answer you gave for #6 (i)? Explain.

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Thermodynamics Curricular Materials

- Preliminary versions and initial testing of worksheets for:
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  - thermochemistry
  - first-law of thermodynamics
  - cyclic processes
  - Carnot cycle
  - entropy
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Preliminary testing in general physics and in junior-level thermal physics course

Conclusions of Initial Study

- Difficulties with fundamental concepts and common idealizations may form a substantial obstacle to students' learning of more advanced principles in thermal physics.

- Increased attention and time to strengthening conceptual base could yield substantial learning dividends in more advanced courses.

Ongoing Work

- Investigation of student understanding of entropy and the second law of thermodynamics in introductory university physics courses
  - Ph.D. work of Warren Christensen at Iowa State
  - draft versions available of two tutorials on entropy and the second law

Second Phase: Upper-level Courses

Research on the Teaching and Learning of Thermal Physics

Funded by Physics Division of NSF

- Investigate student learning of statistical thermodynamics
- Probe evolution of students' thinking from introductory through advanced-level course
- Develop research-based curricular materials

In collaboration with John Thompson, University of Maine

Conclusion

- Many research-based resources are available to help students learn topics in thermodynamics, using "guided-inquiry" methods.
- Ongoing research at both introductory and advanced levels promises to yield further innovations in curriculum and pedagogy, and improvements in instruction.