Students' Reasoning Regarding Fundamental Concepts in Thermodynamics: Implications for Instruction

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Supported in part by NSF DUE #9981140 and PHY-#0406724

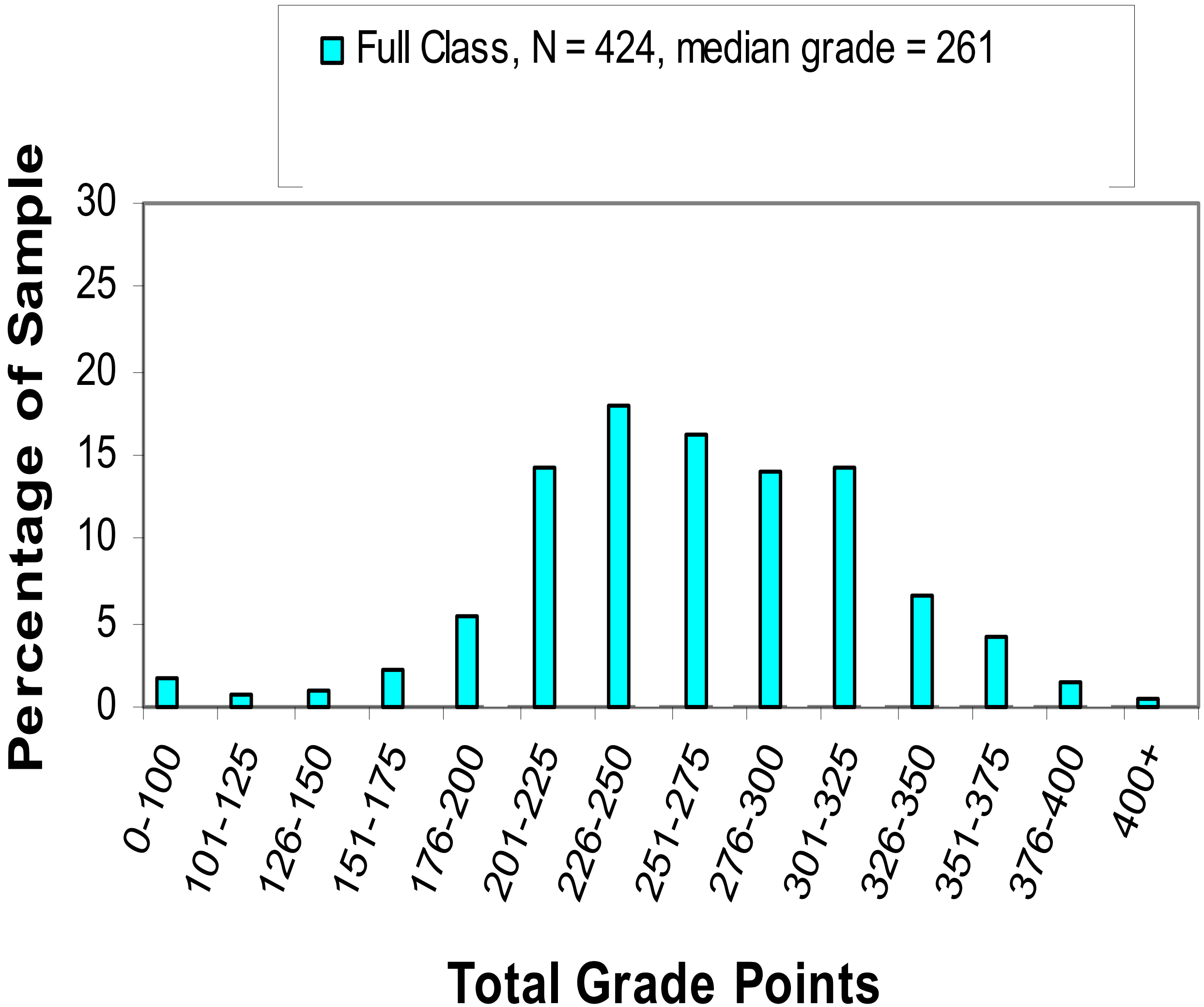
Student Learning of Thermodynamics

- 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 now there has been only limited study of thermodynamics knowledge of students in introductory (first-year) calculus-based general physics course.

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

- Investigation of second-semester calculus-based physics course (mostly engineering students).
- Written diagnostic questions administered last week of class in 1999, 2000, and 2001 (N_{total} = 653).
- 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*

Grade Distributions: Interview Sample vs. Full Class



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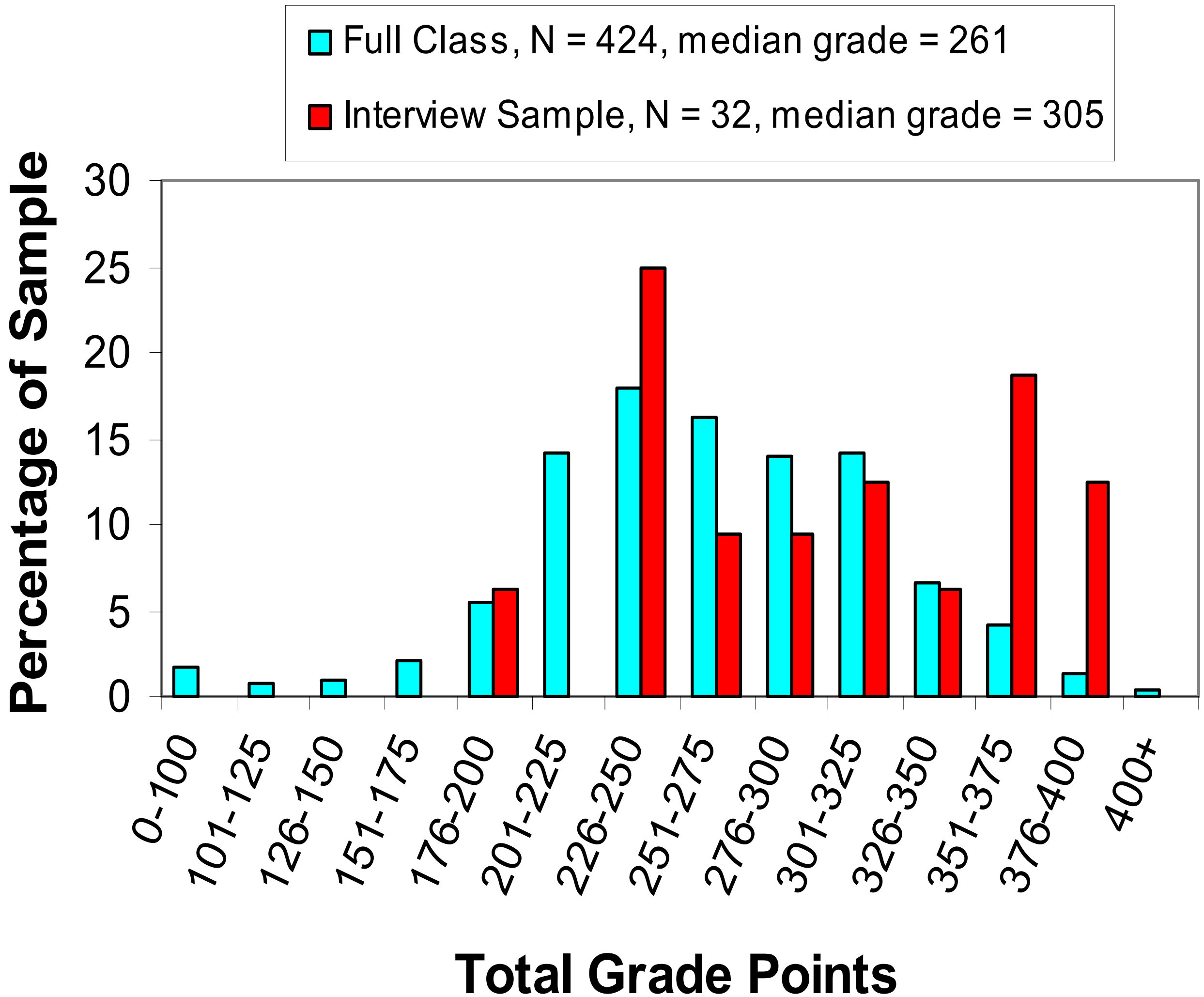

***Interview Sample*:**

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

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.
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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?

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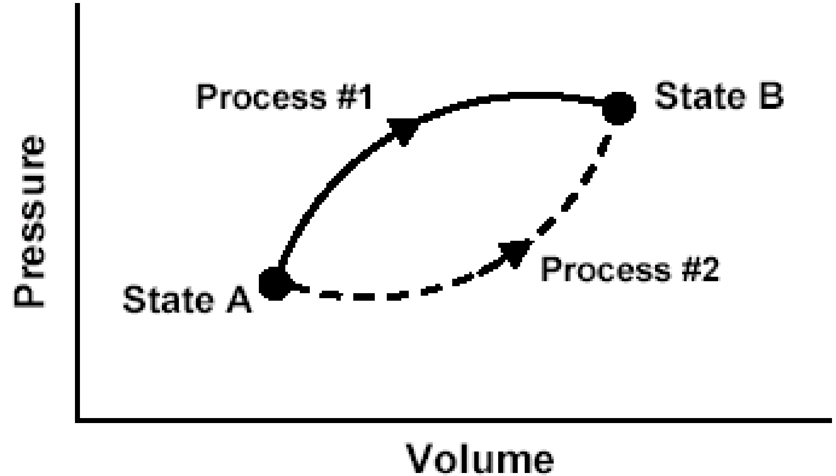

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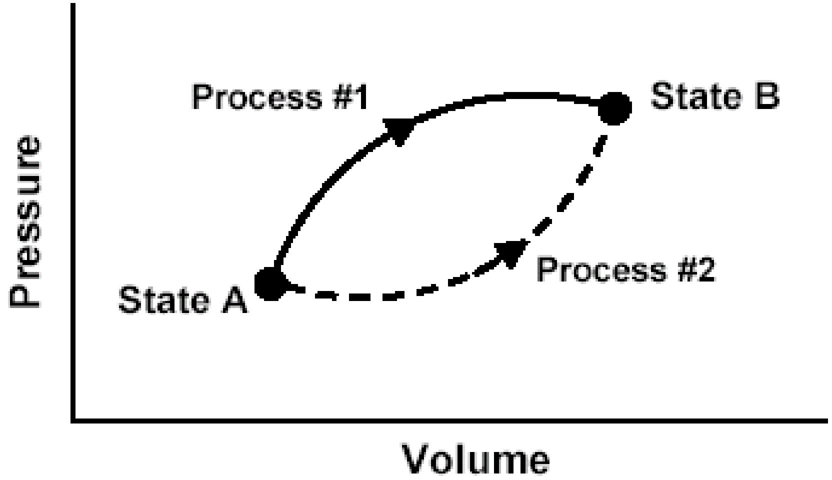

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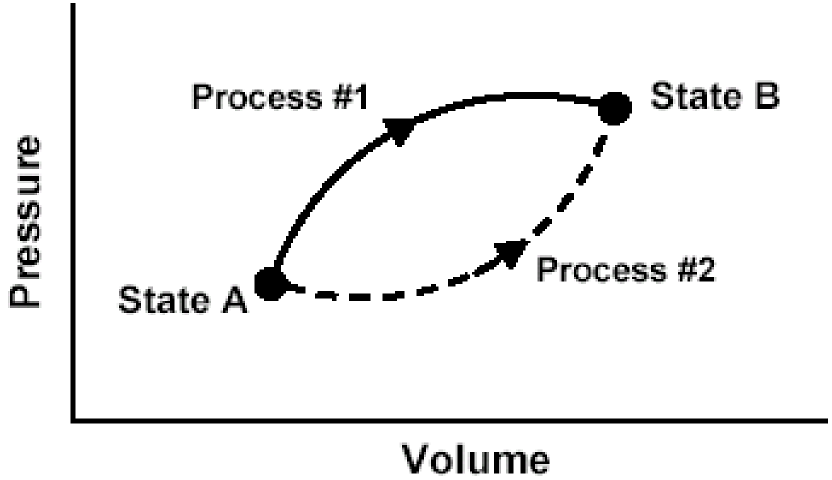
$$\Delta U_1 = \Delta U_2$$



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Students seem to have adequate grasp of state-function concept

- Consistently high percentage (70-90%) of correct responses on written question, with good explanations.

- Interview subjects displayed good understanding of state-function idea.

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

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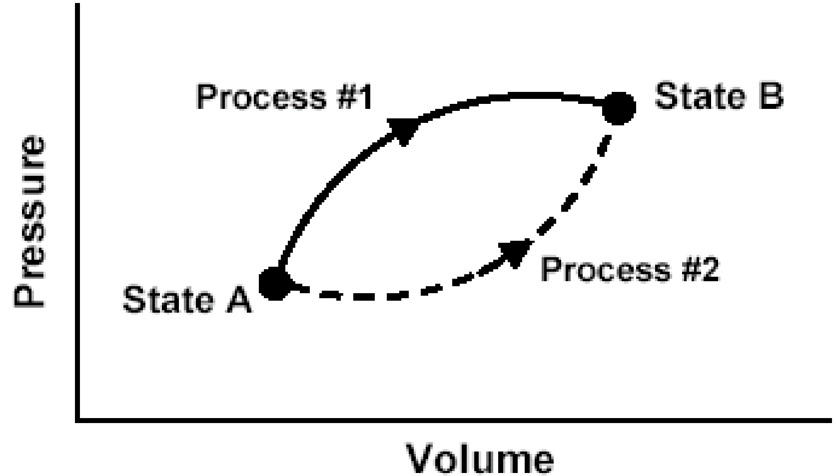

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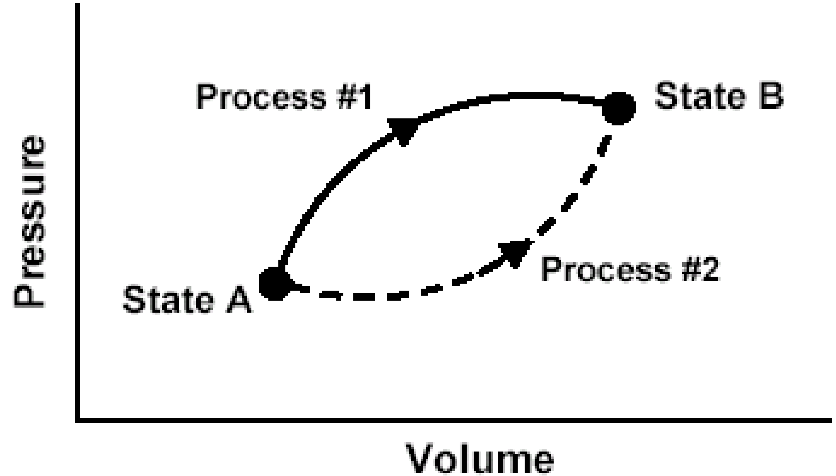

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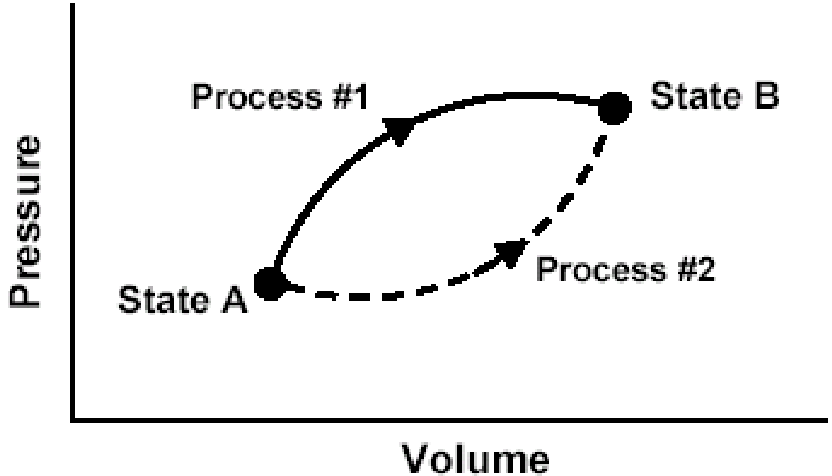

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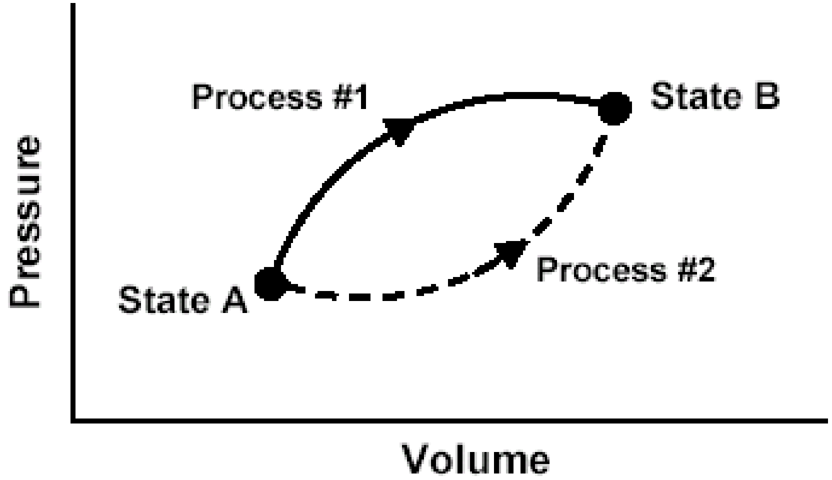

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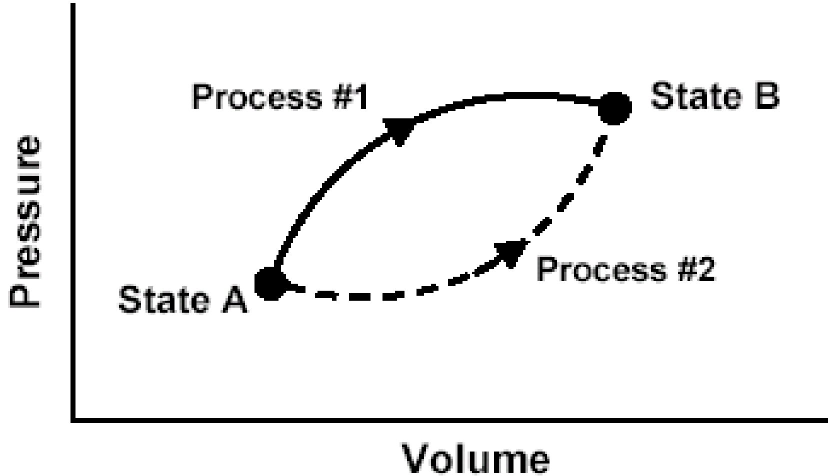

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Responses to Diagnostic Question #1
(Work question)

	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002 Interview Sample** (*N*=32)
$W_1 > W_2$				
$W_1 = W_2$				
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	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
$W_1 = W_2$	**25%**	**26%**	**35%**	**22%**
Because work is independent of path	*	**14%**	**23%**	**22%**
Other reason, or none	*	**12%**	**13%**	**0%**

*explanations not required in 1999

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*."

→ **Many students come to associate work with properties (and descriptive phrases) only used by instructors in connection with state functions.**

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Confusion with mechanical work done by conservative forces?

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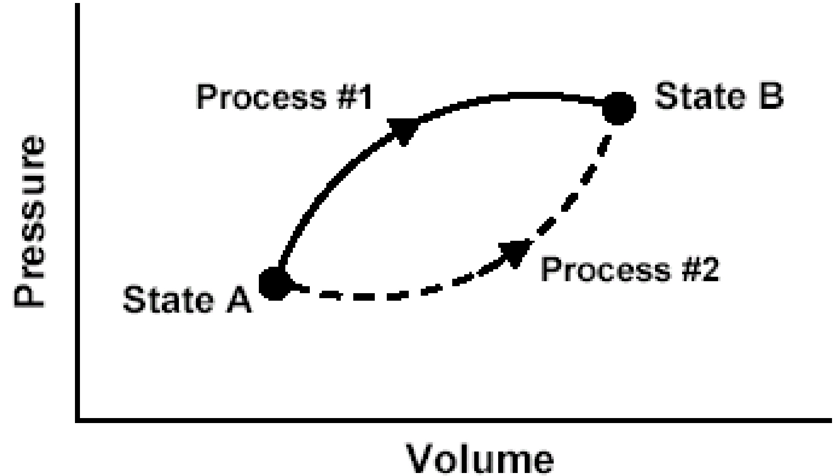

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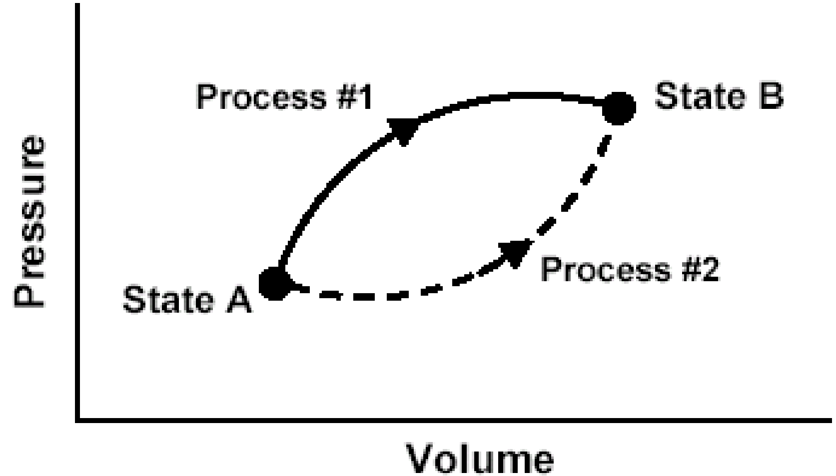

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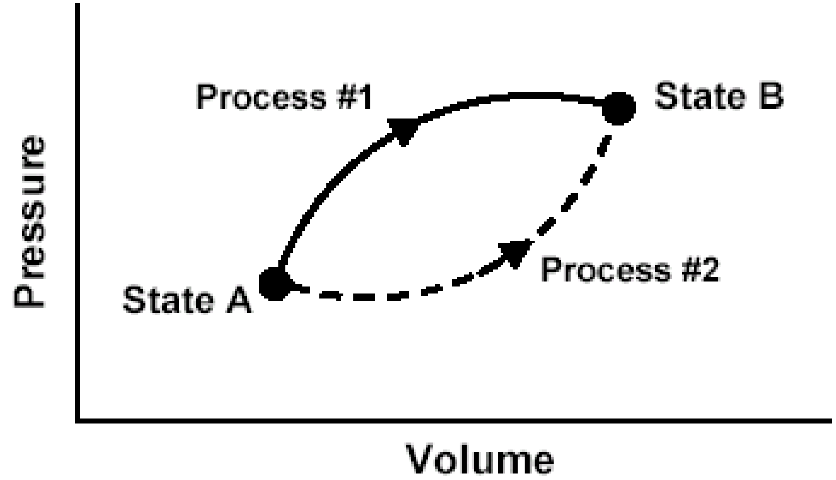
Change in internal energy is the same for Process #1 and Process #2.



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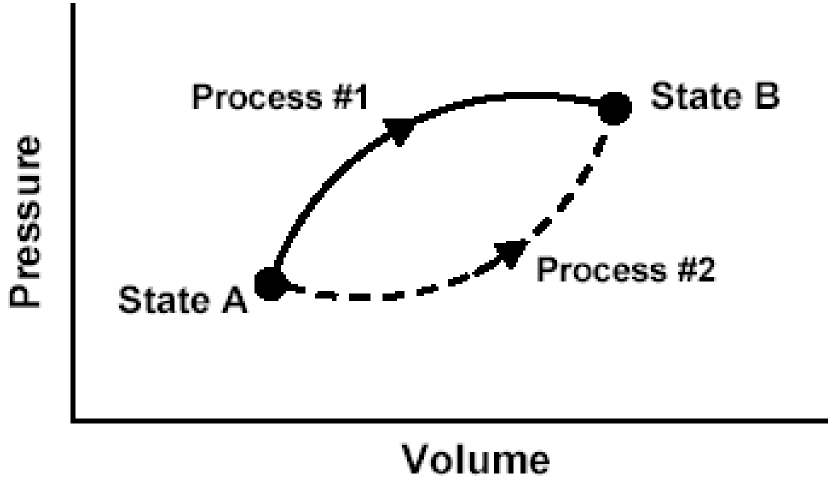
The system does more work in Process #1, so it must absorb more heat to reach same final value of internal energy:
$Q_1 > Q_2$



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Responses to Diagnostic Question #2

(Heat question)

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$Q_1 > Q_2$				
$Q_1 = Q_2$				
$Q_1 < Q_2$				

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*."

➢ **Almost 150 students offered arguments similar to these either in their written responses or during the interviews.**

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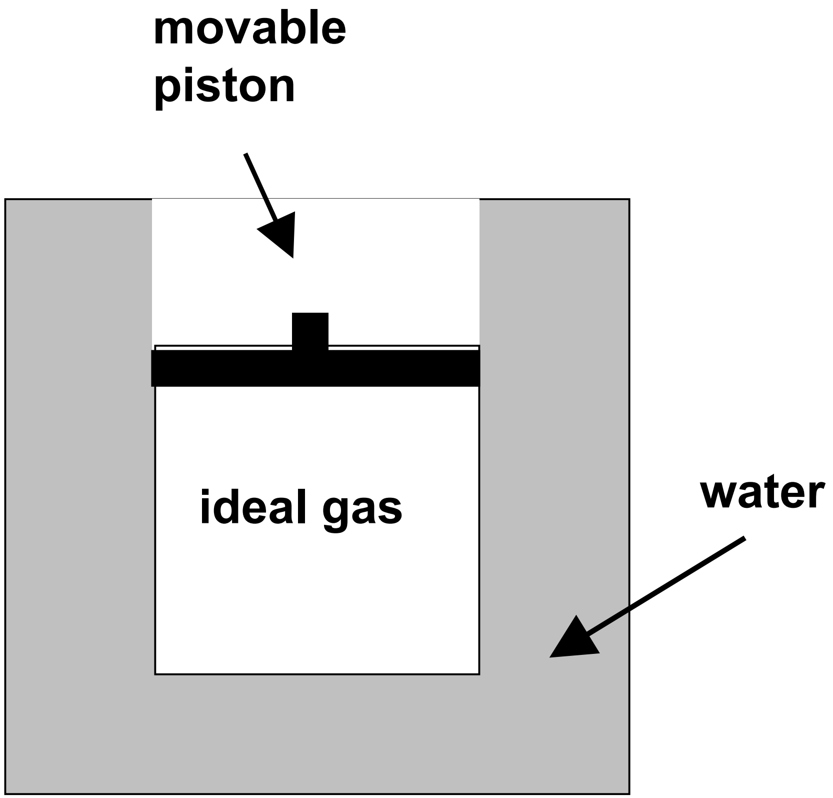
Interview Questions

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

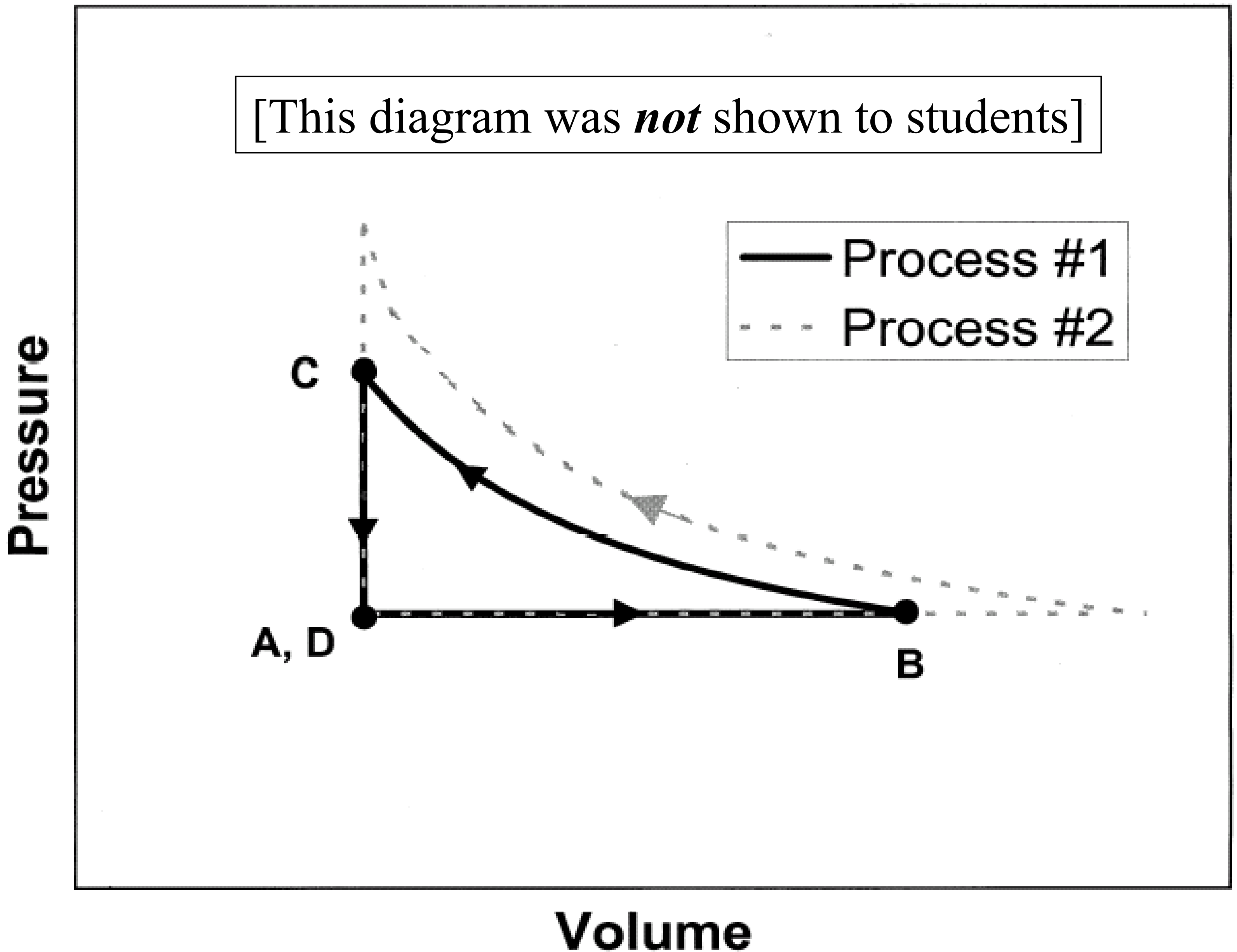
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

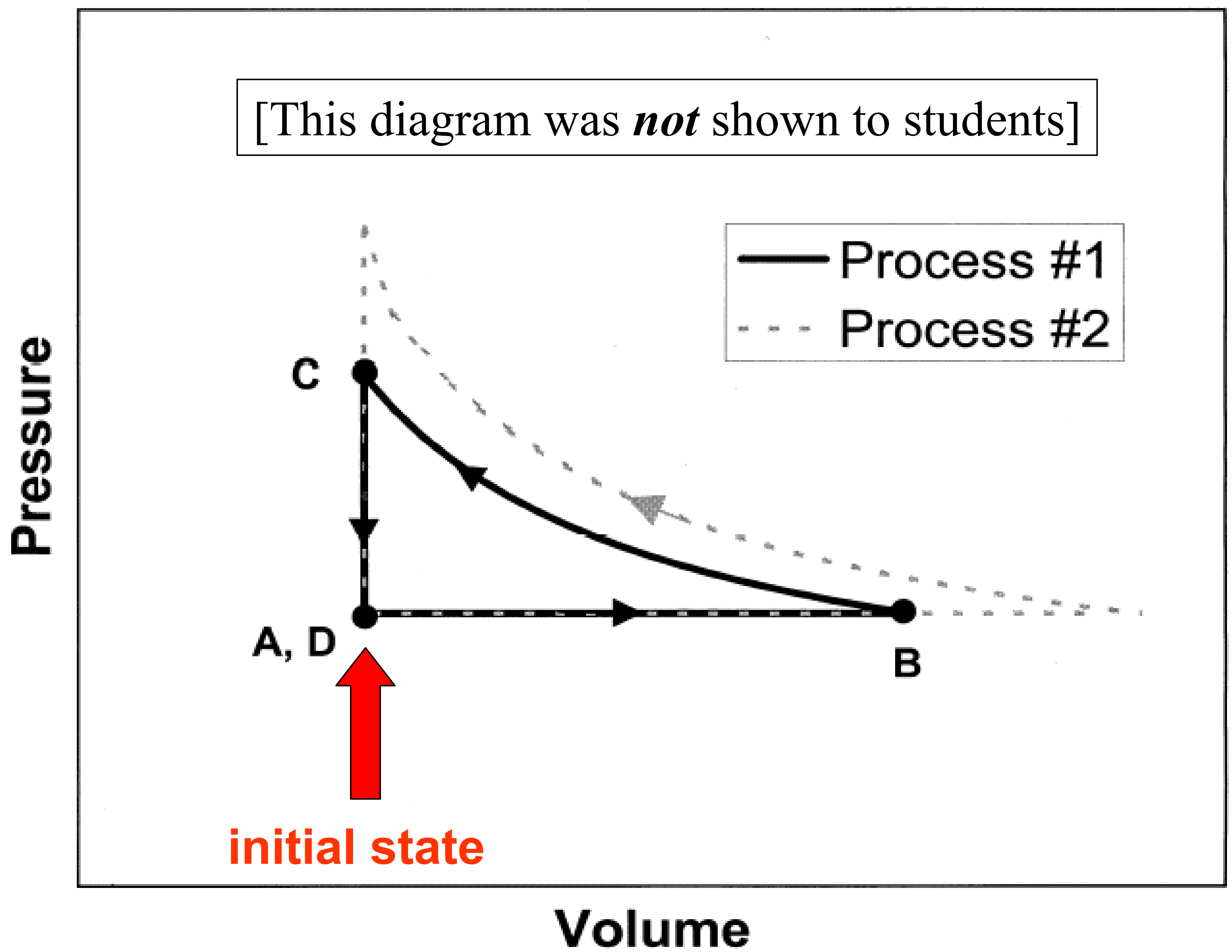
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature



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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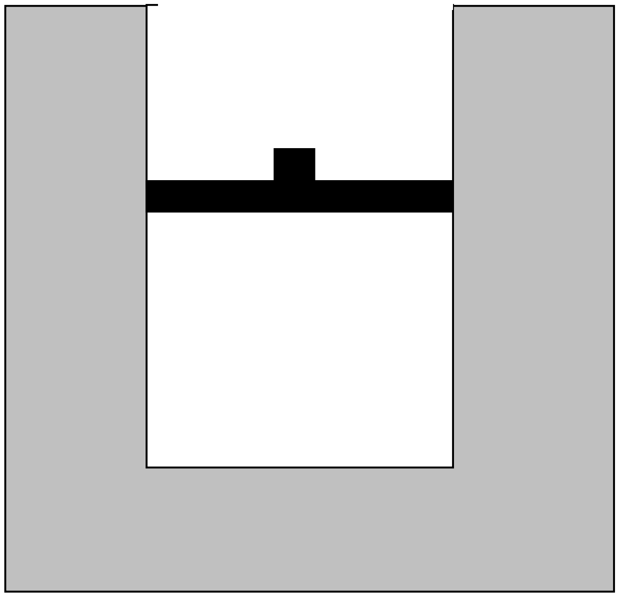
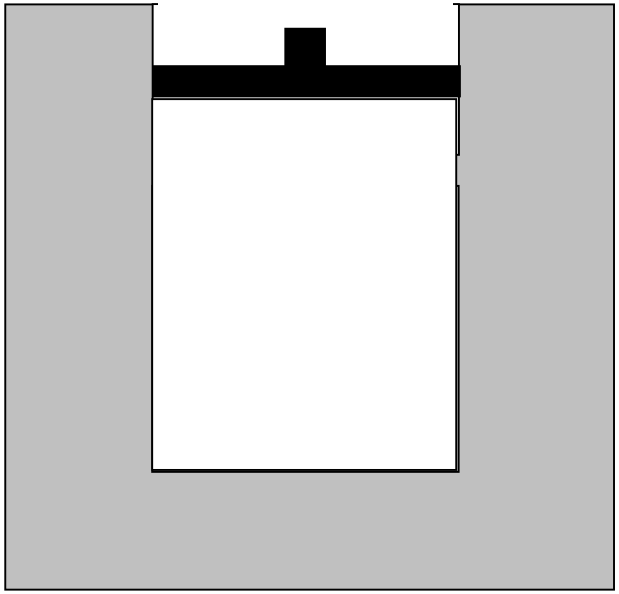
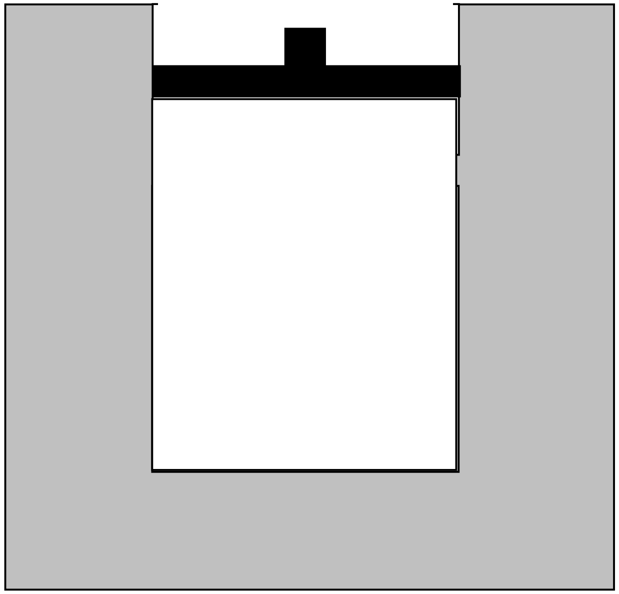
Process #1
Process #2
C
A, D
B
initial state
Pressure
Volume

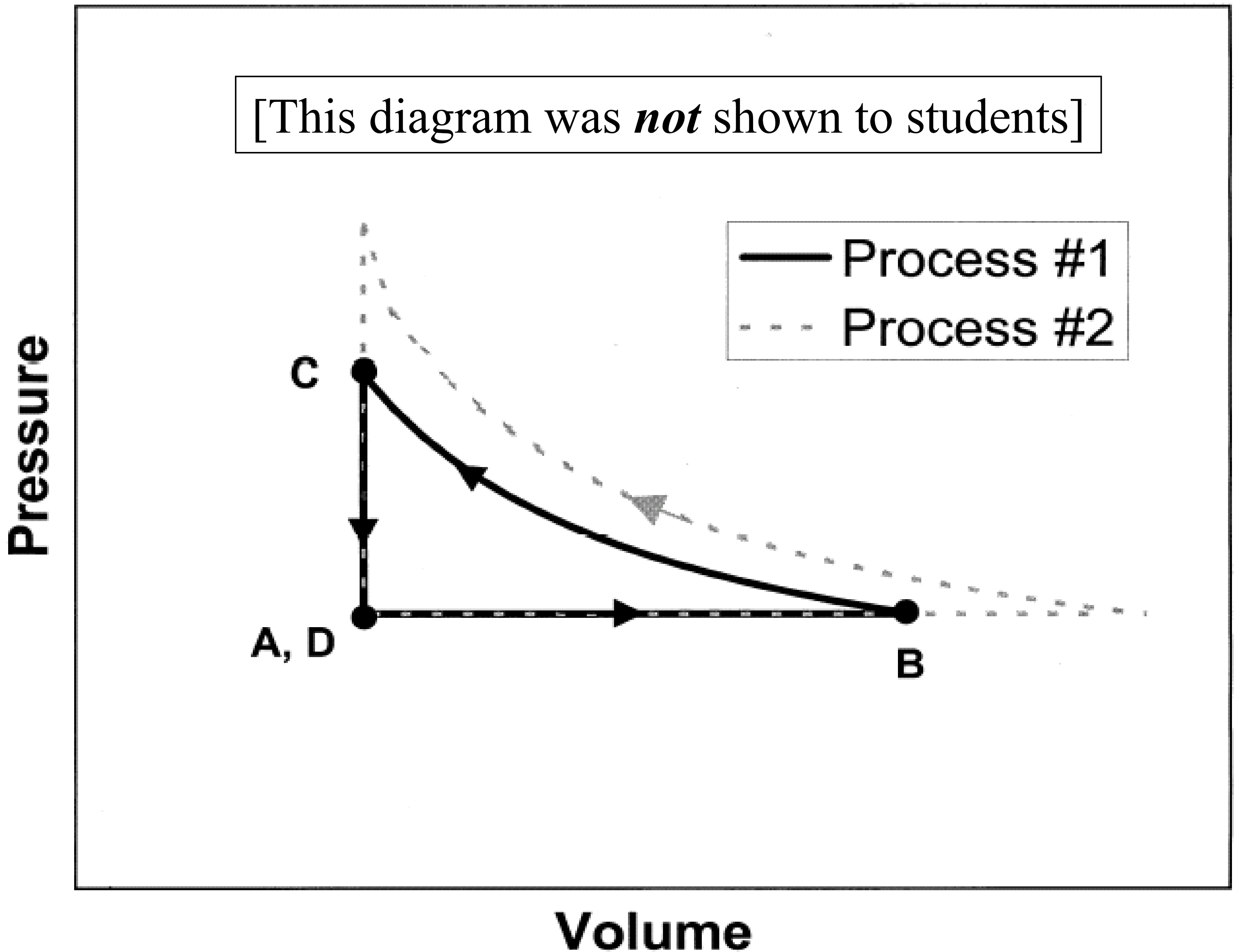
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.





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

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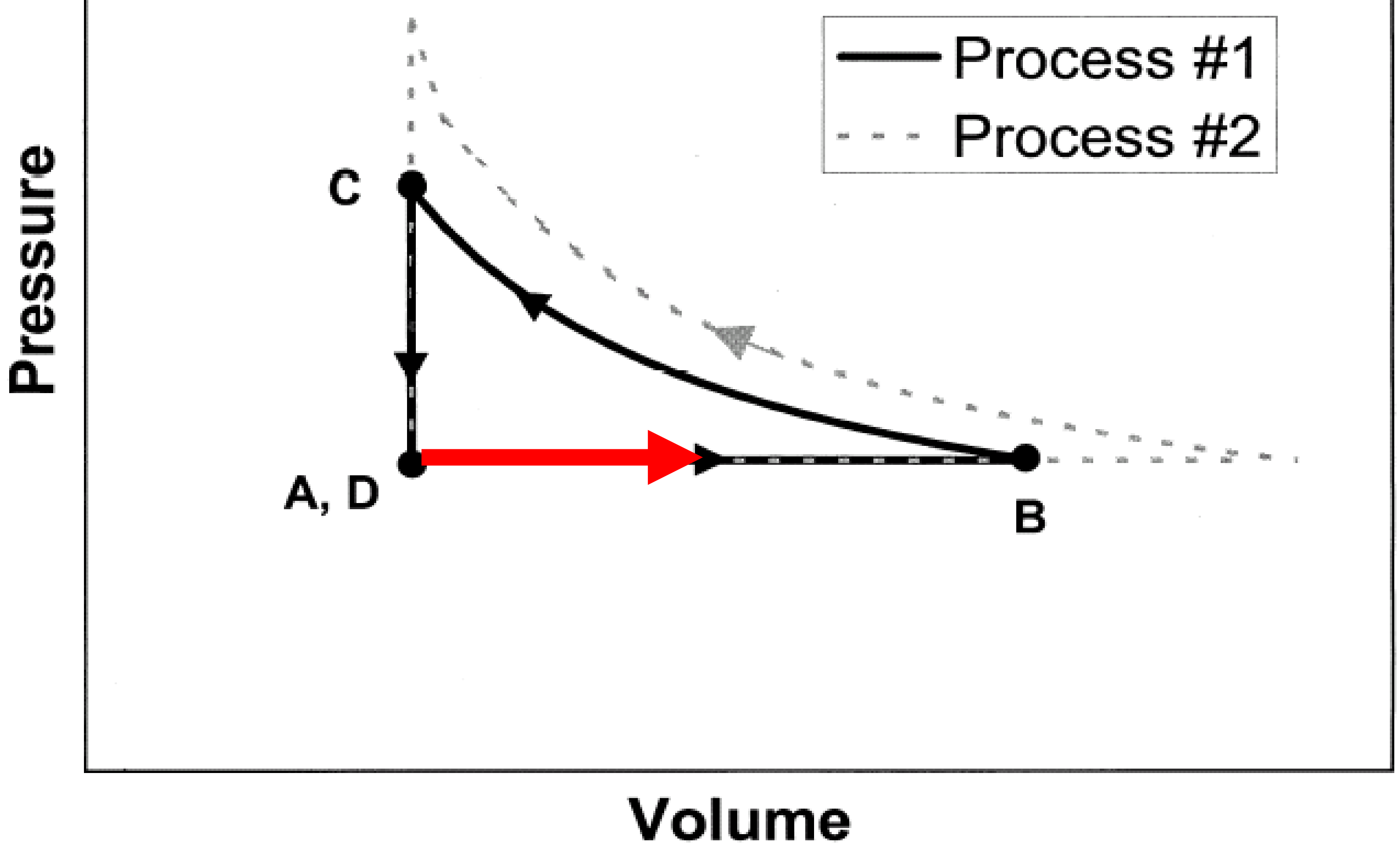

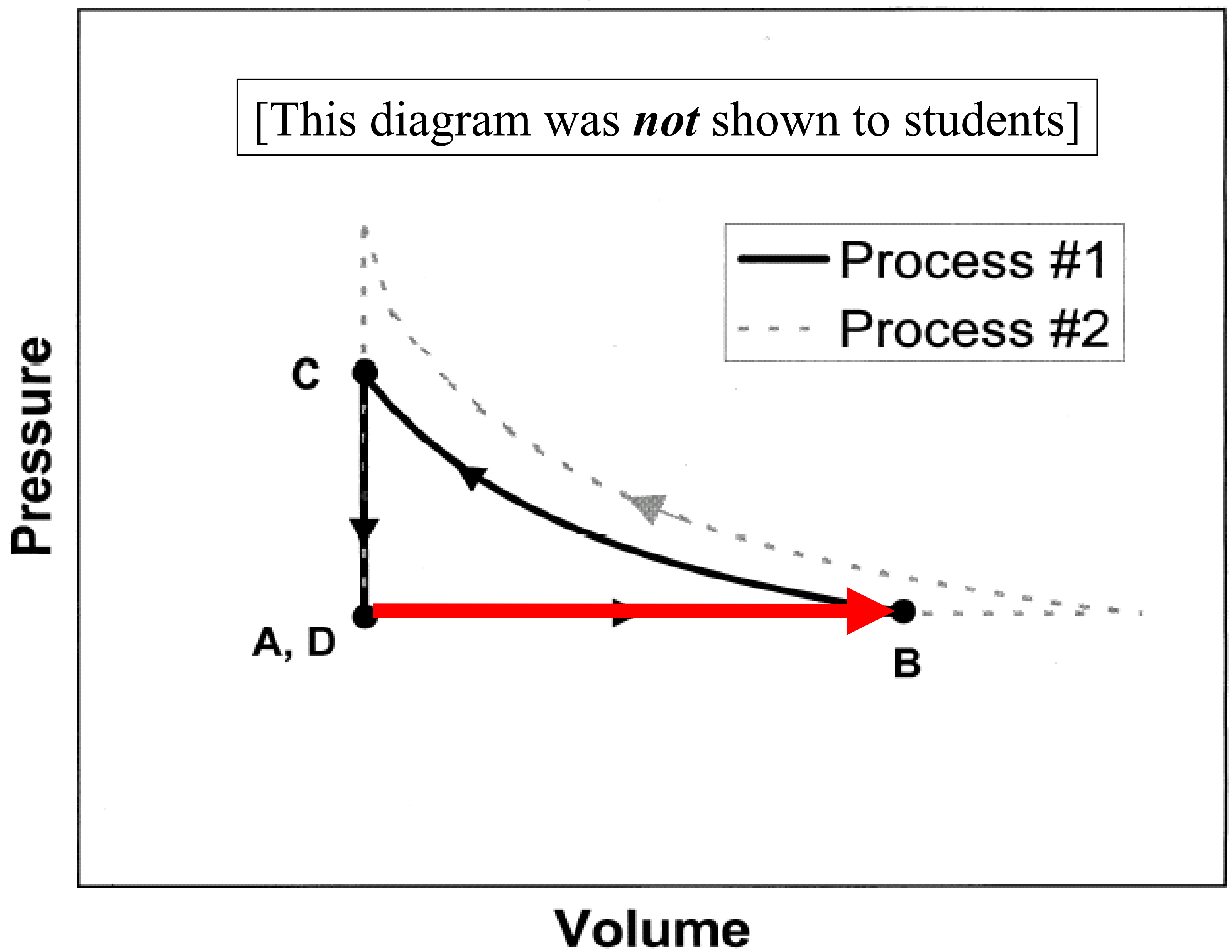
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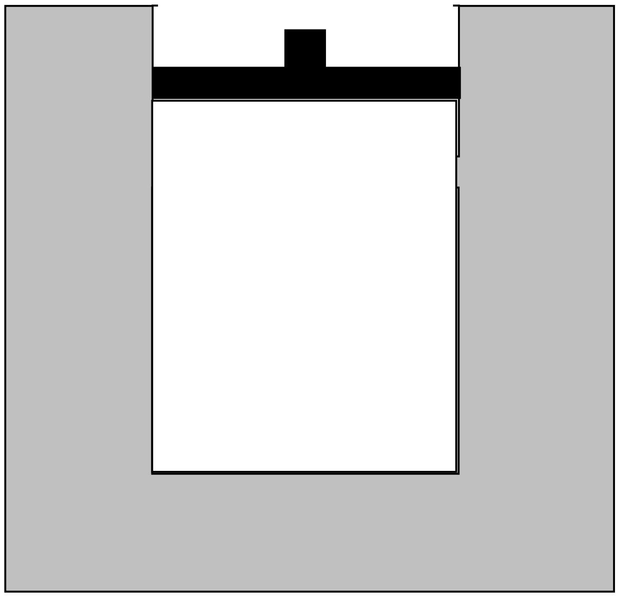

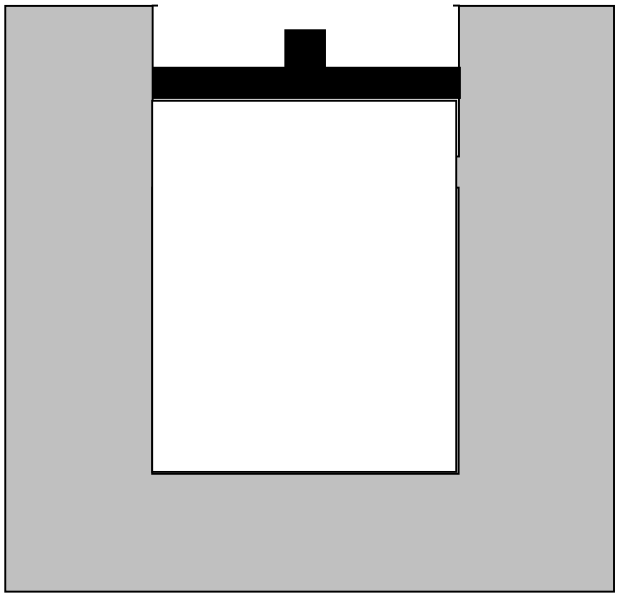

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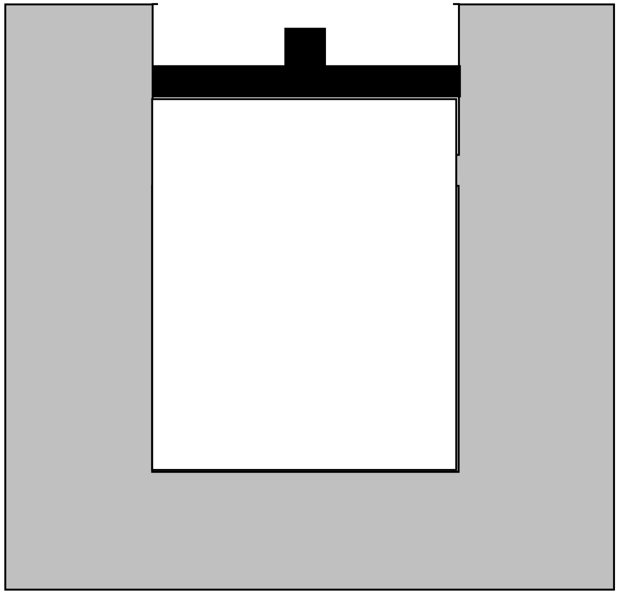

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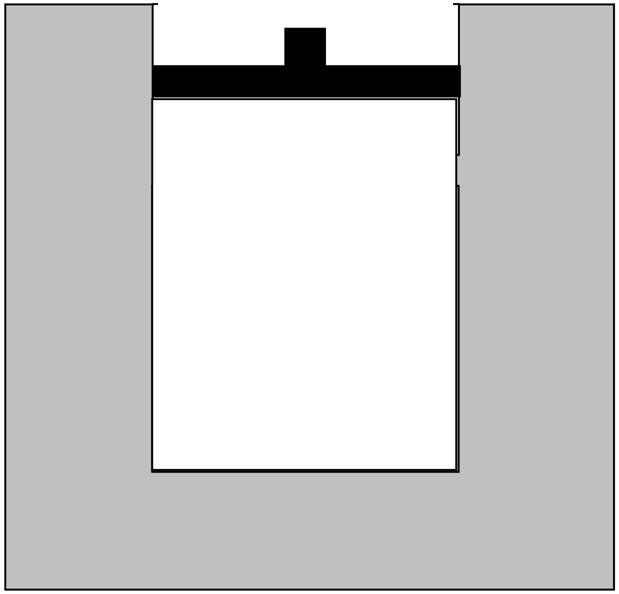

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Results on Question #1

(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."

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

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

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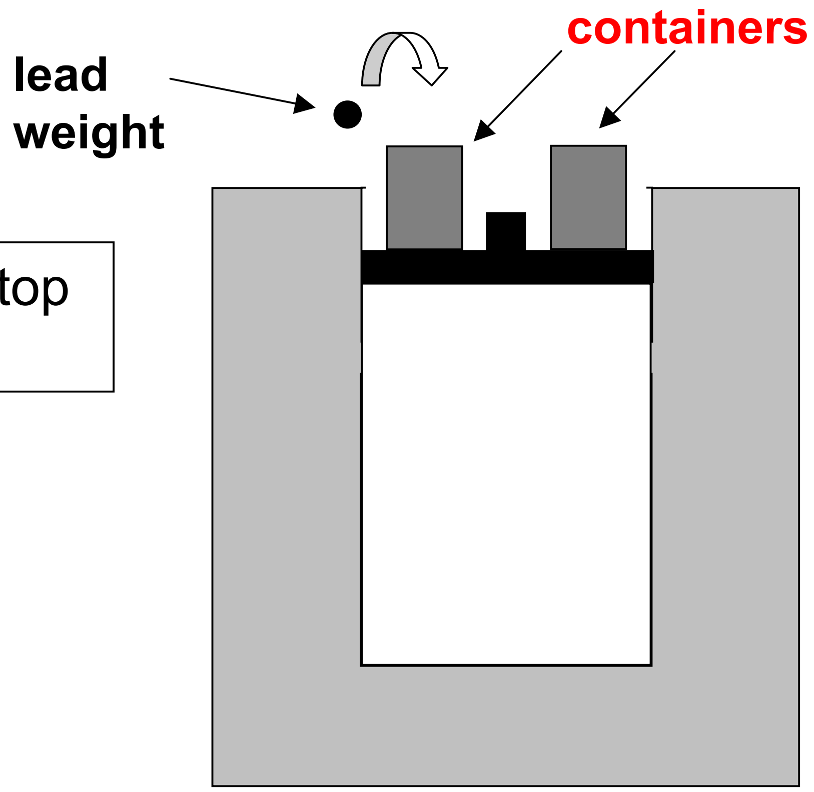
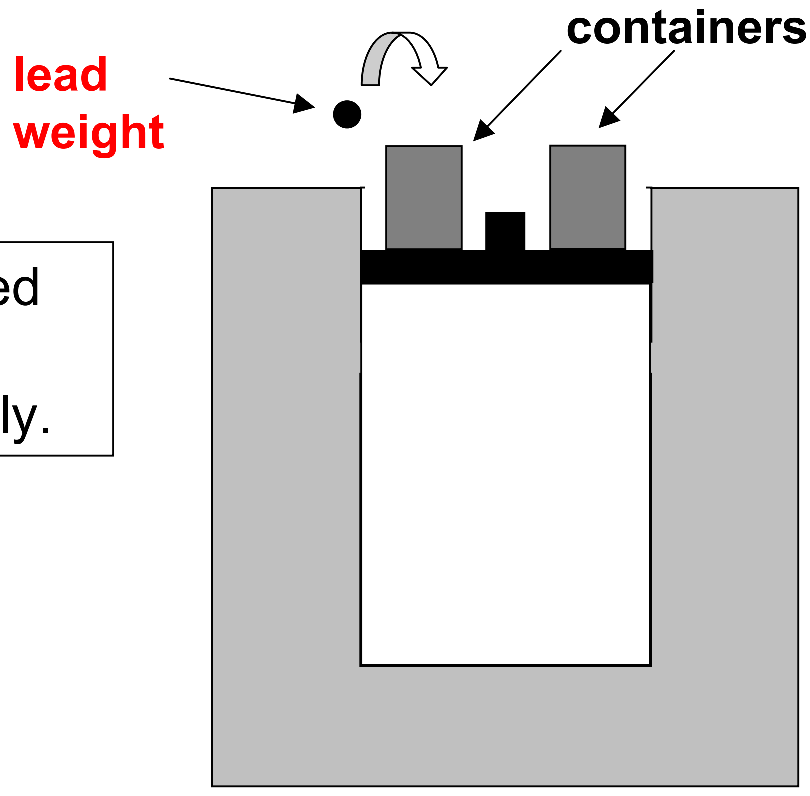
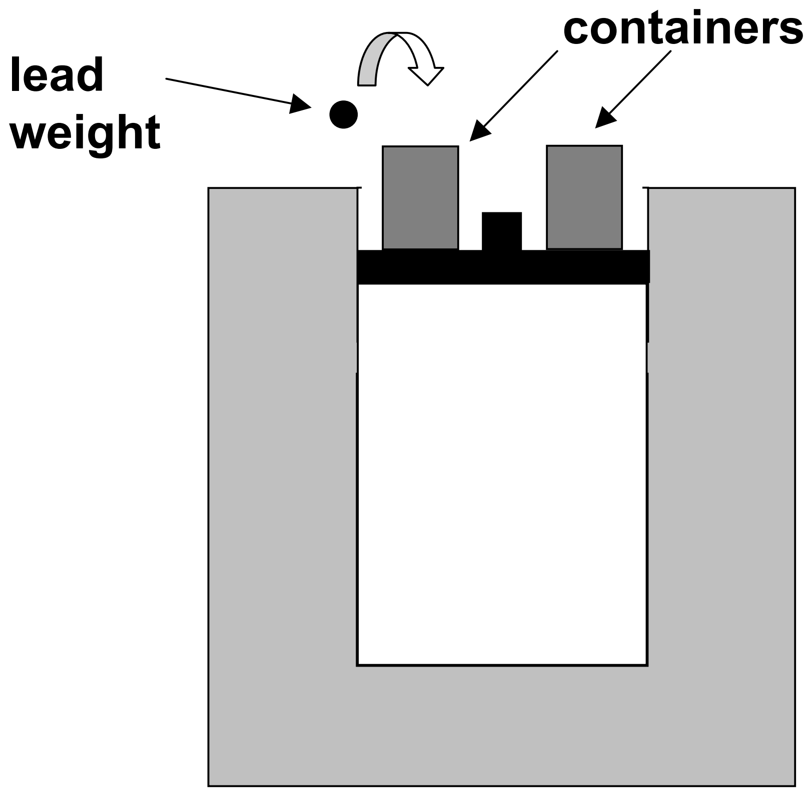
Additional questions showed that half the sample did not realize that some energy was transferred away from gas due to expansion.

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

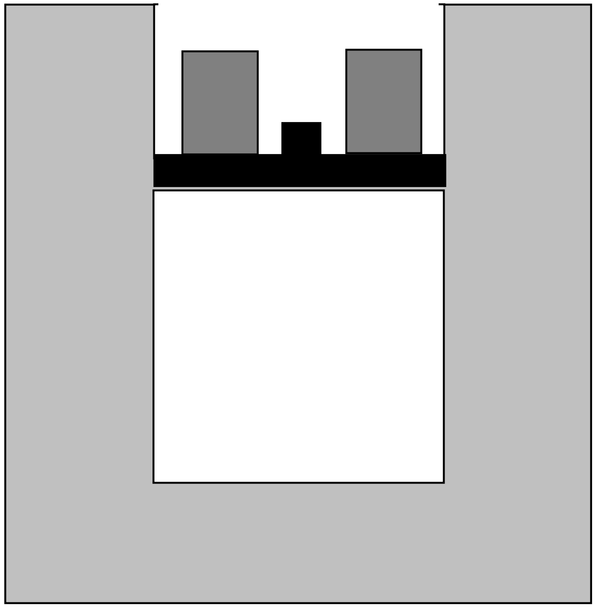


Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly.

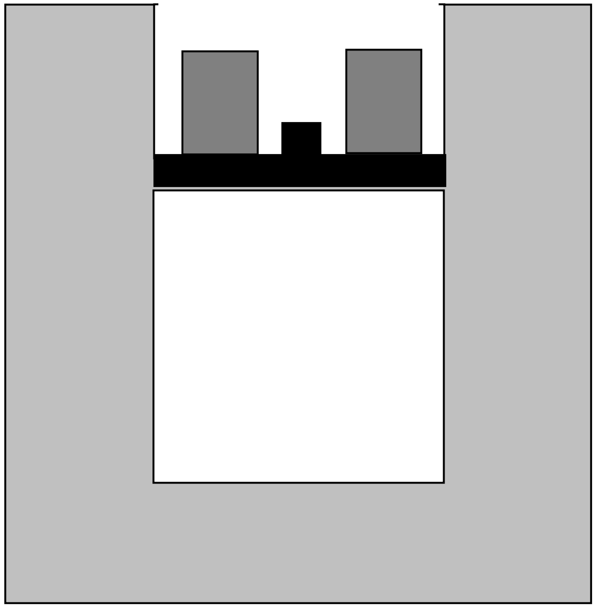




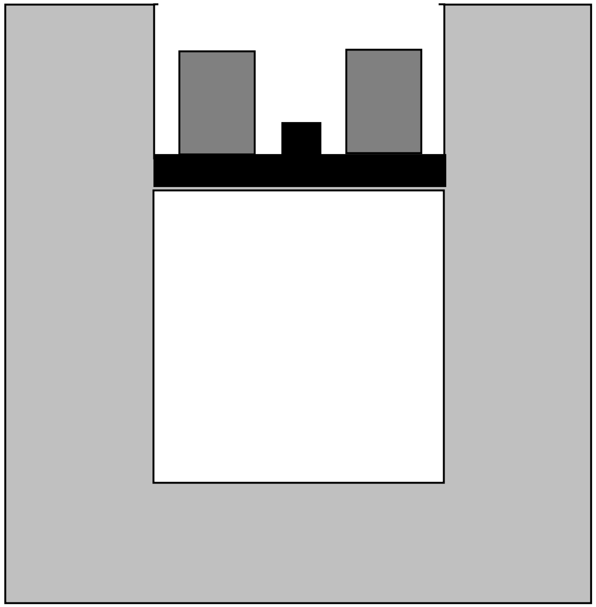
containers
lead
weight

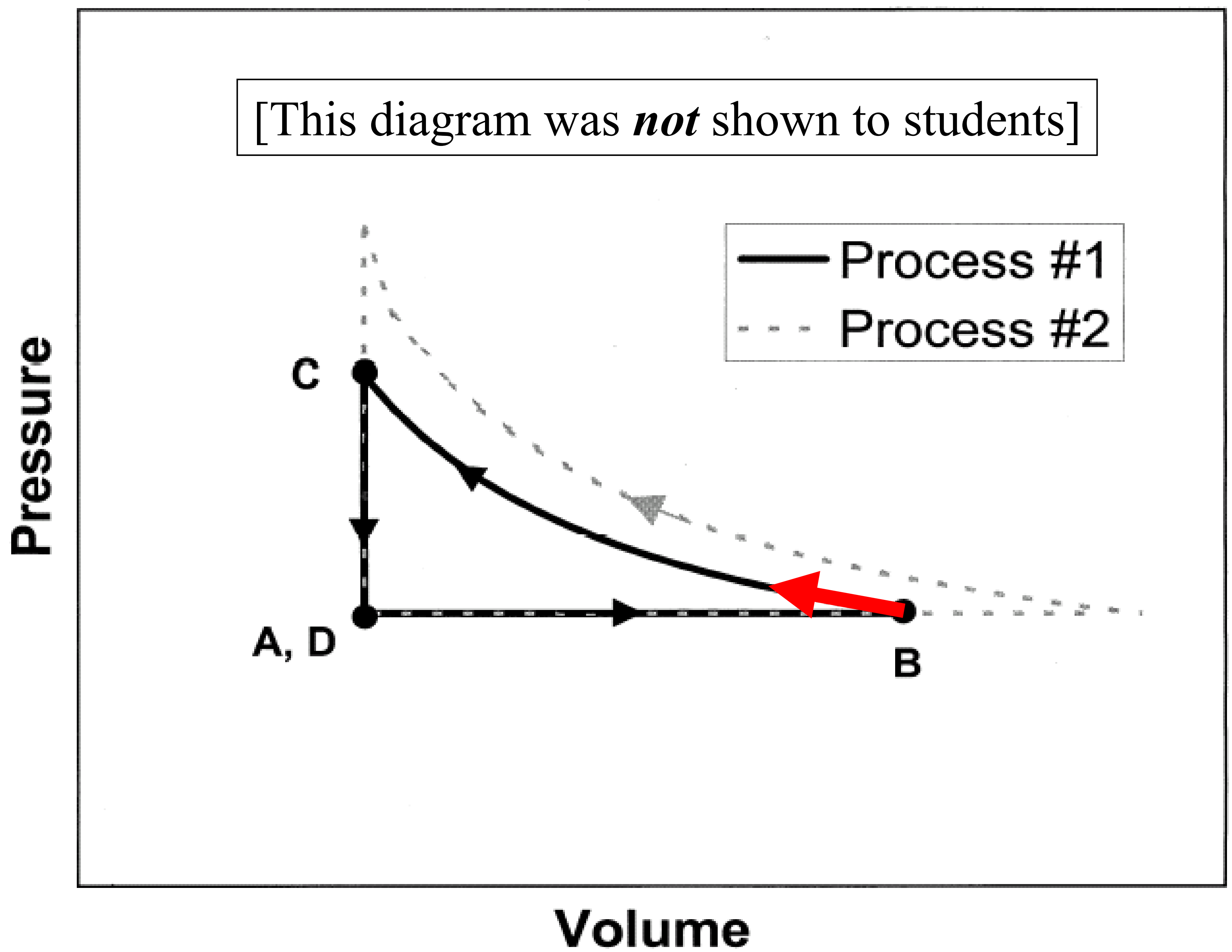


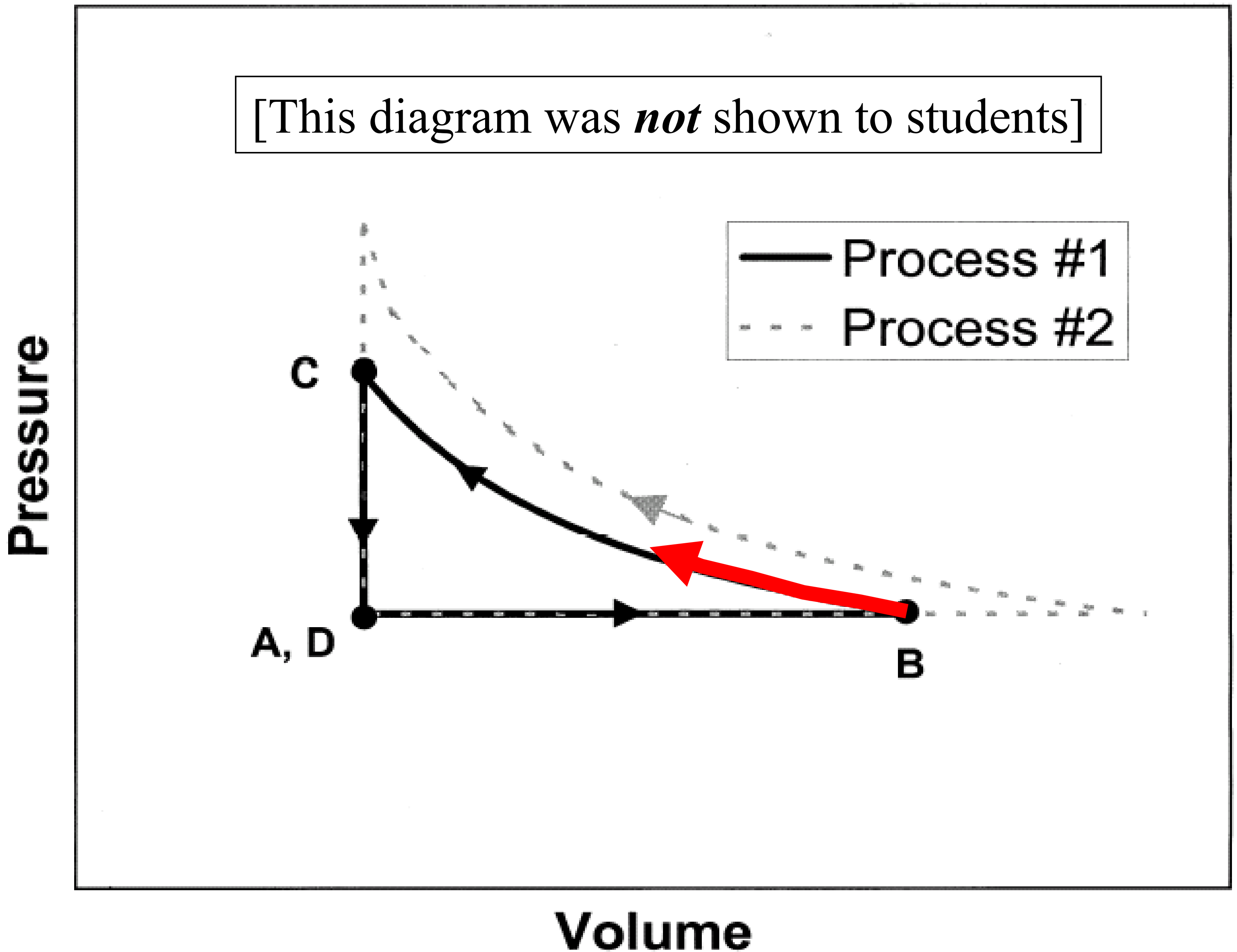
While this happens the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*.

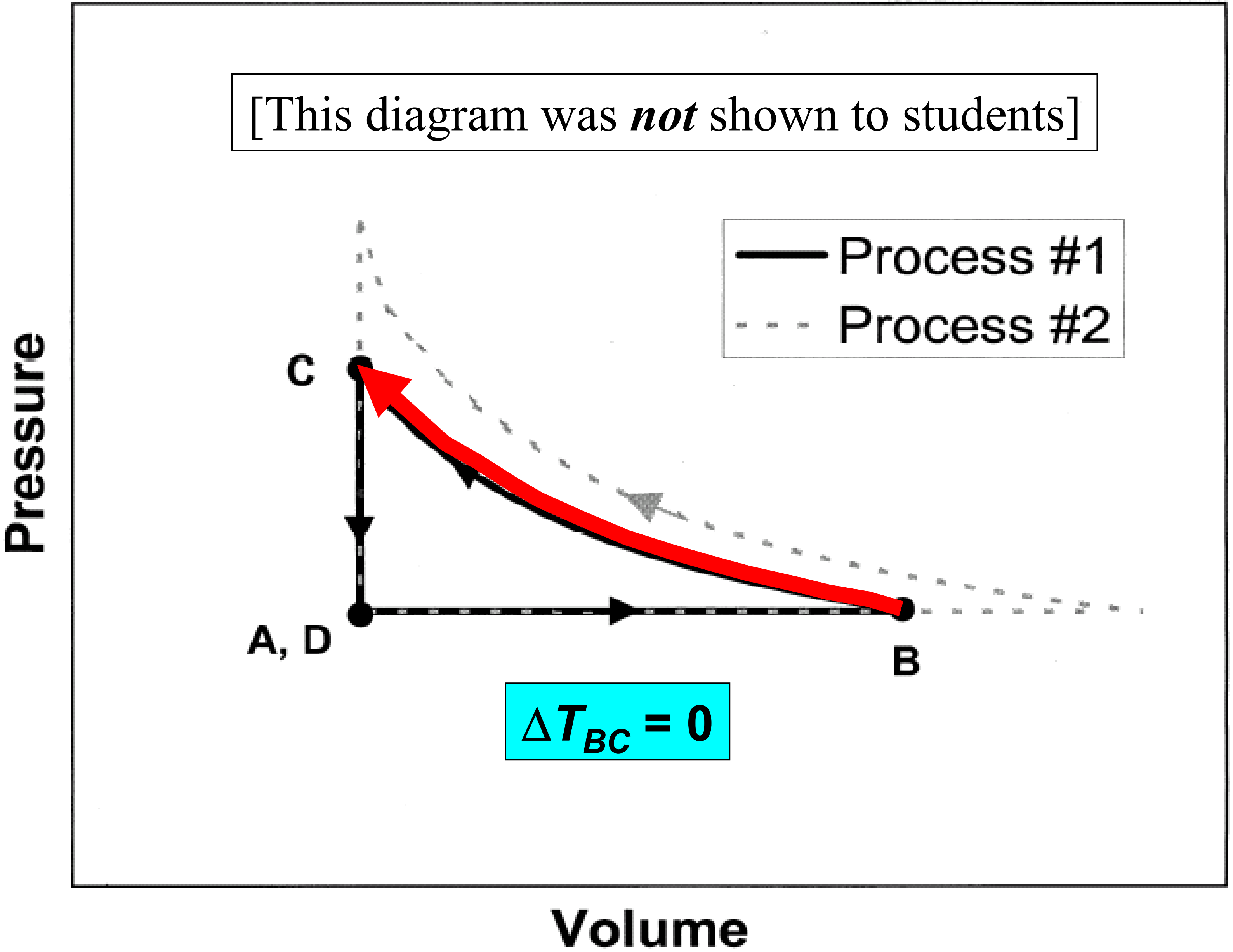


At time ***C*** we stop adding lead weights to the container and the piston stops moving. The piston is now at exactly the same position it was at time ***A*** .

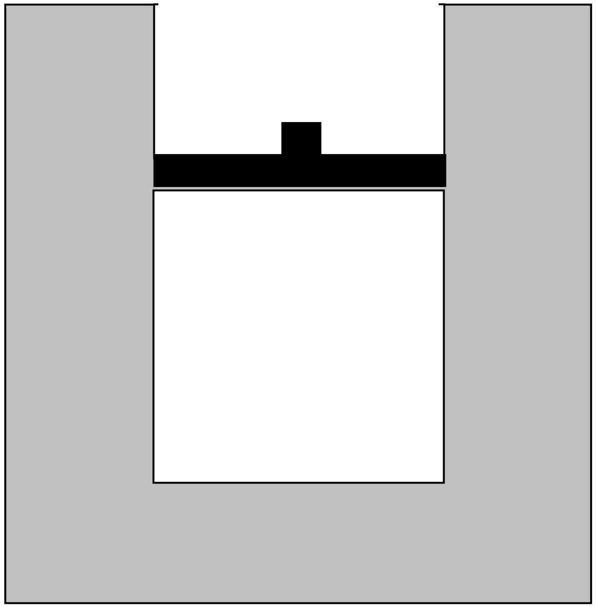



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

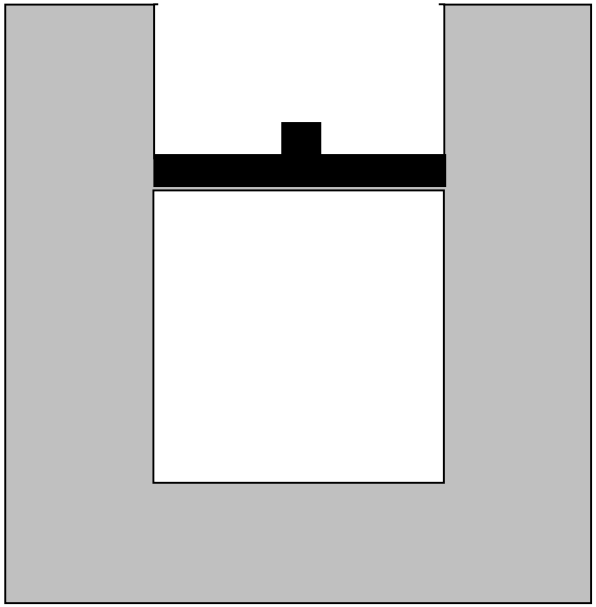

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume


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

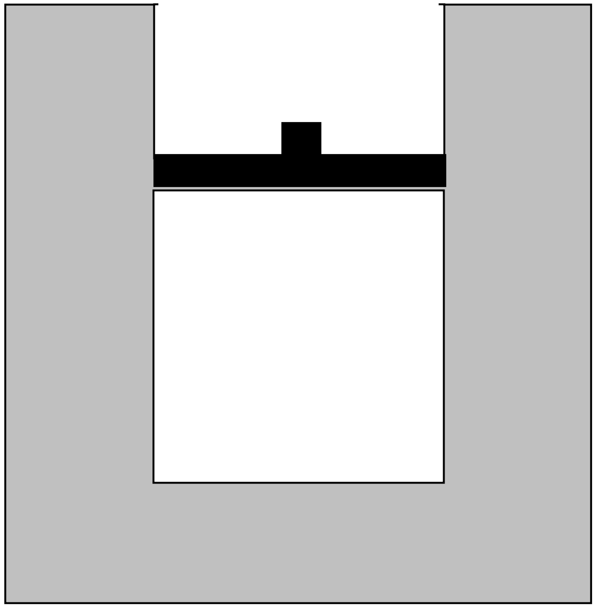
Now, the piston is locked into place so it *cannot move*, and the weights are removed from the piston.



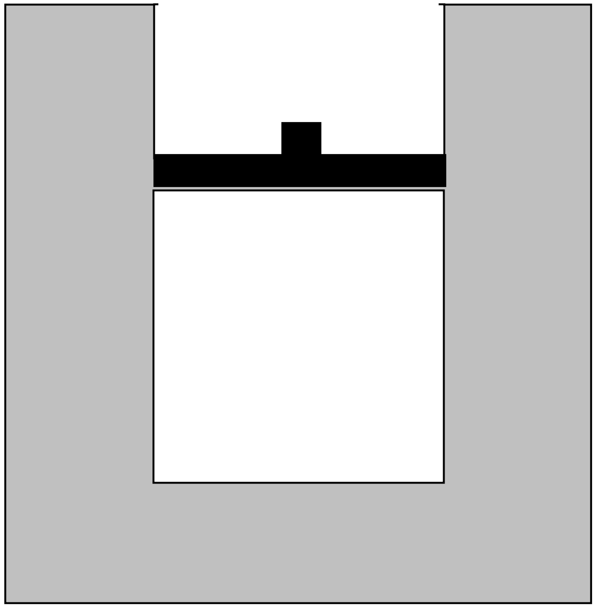
The system is left to sit in the room for many hours.

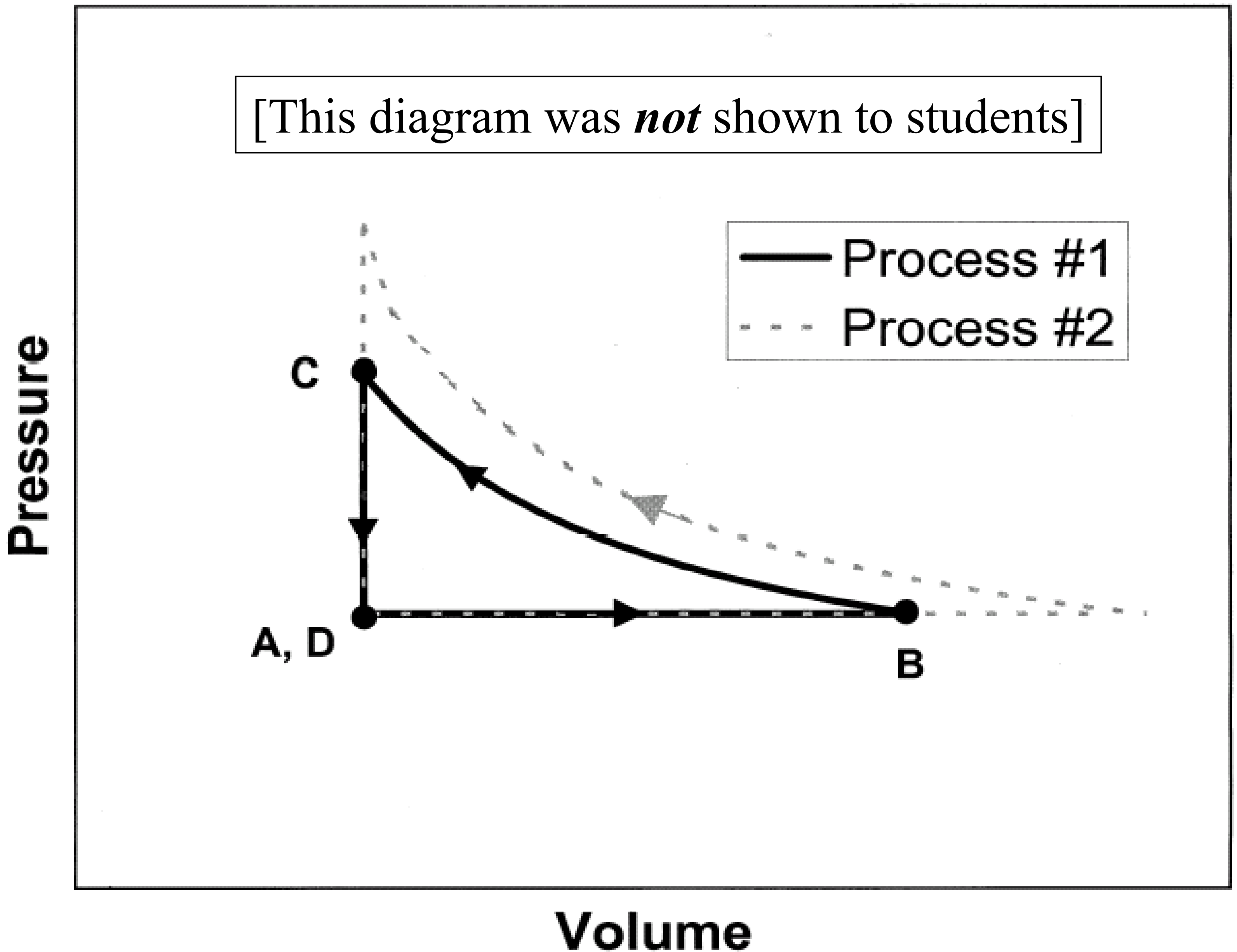


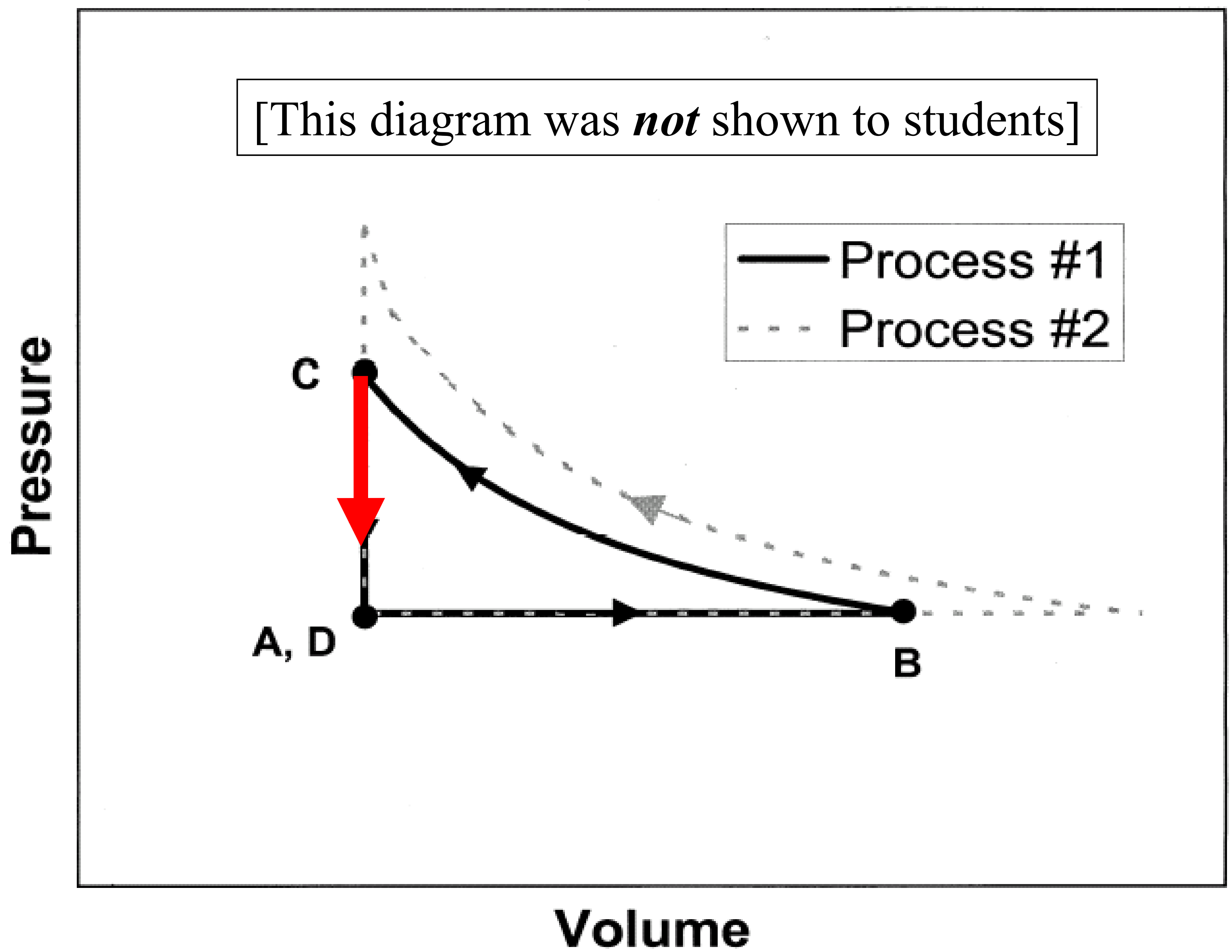
Eventually the entire system cools back down to the same room temperature it had at time ***A***.



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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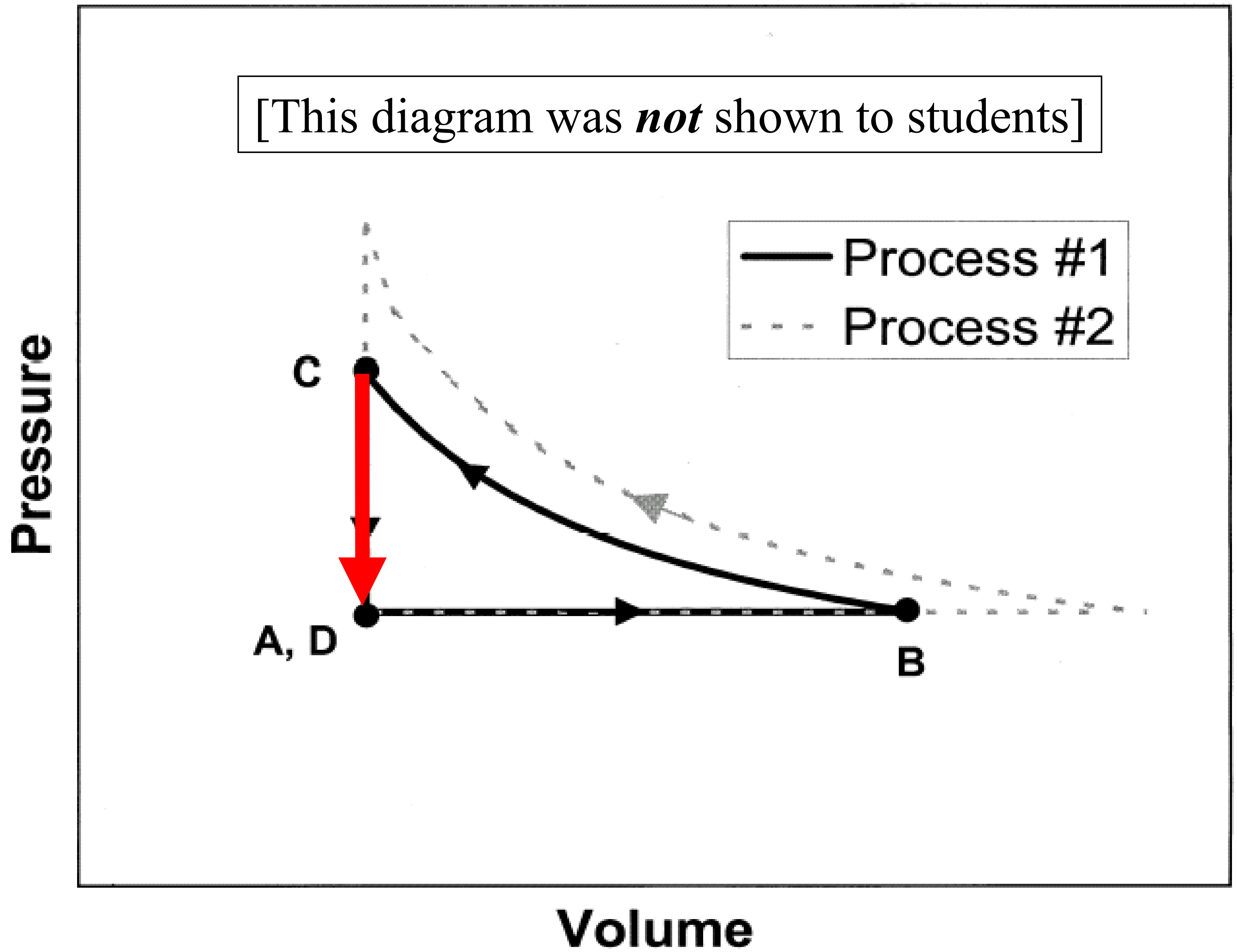
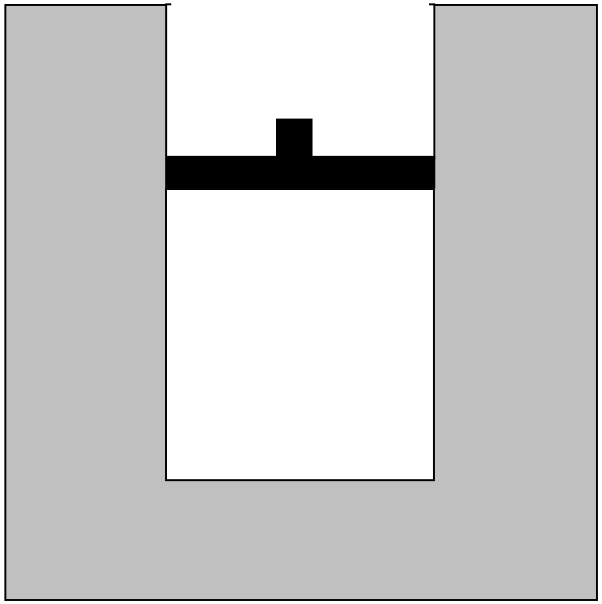
Process #1
Process #2
C
A, D
B
Pressure
Volume

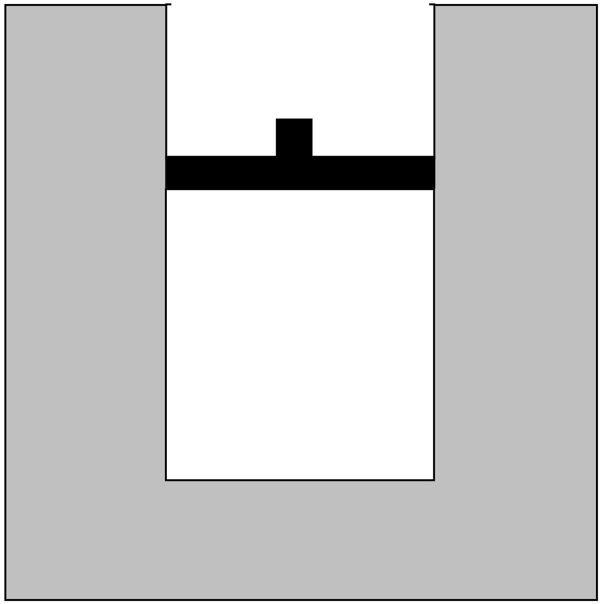

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



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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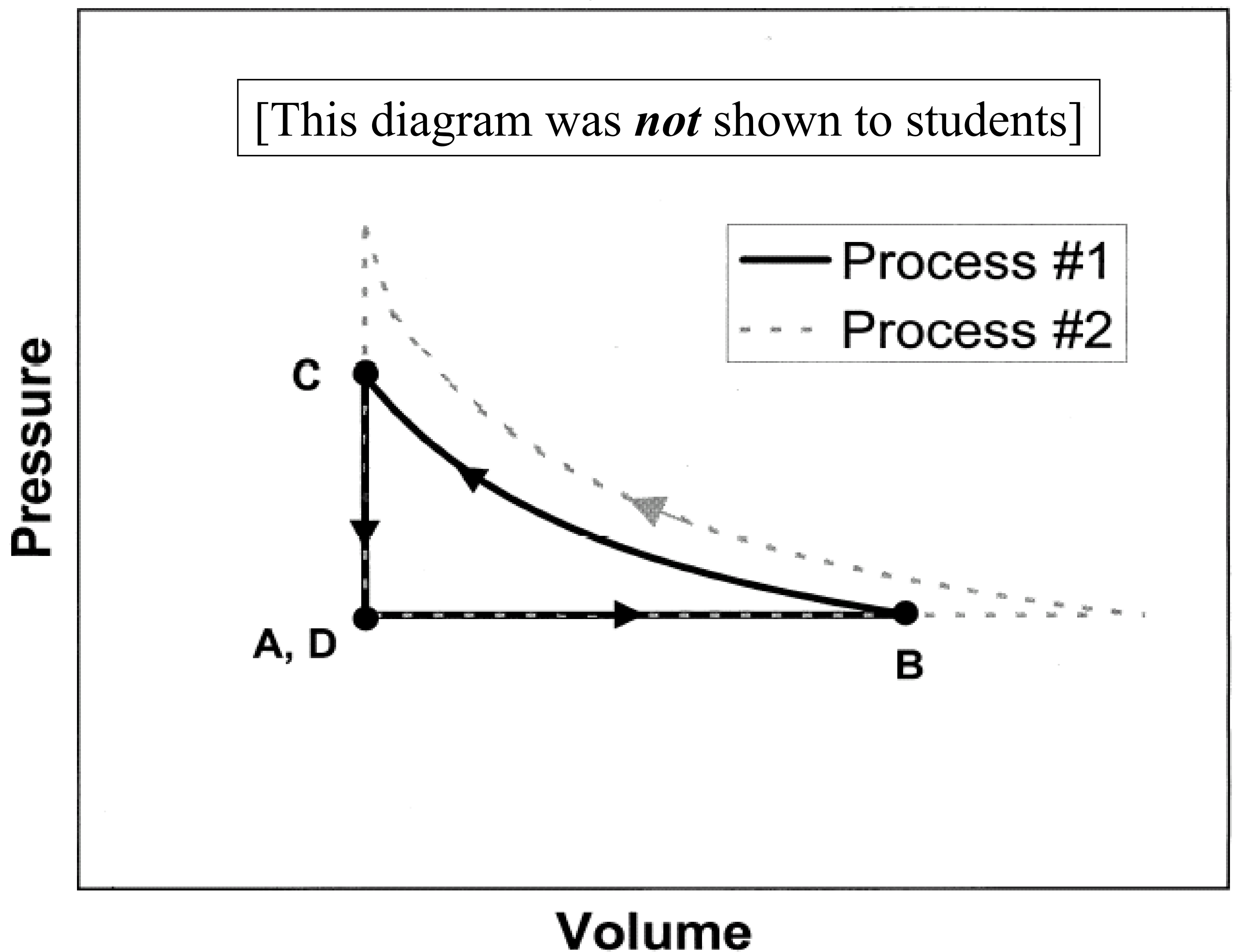
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Process #1
Process #2
C
A, D
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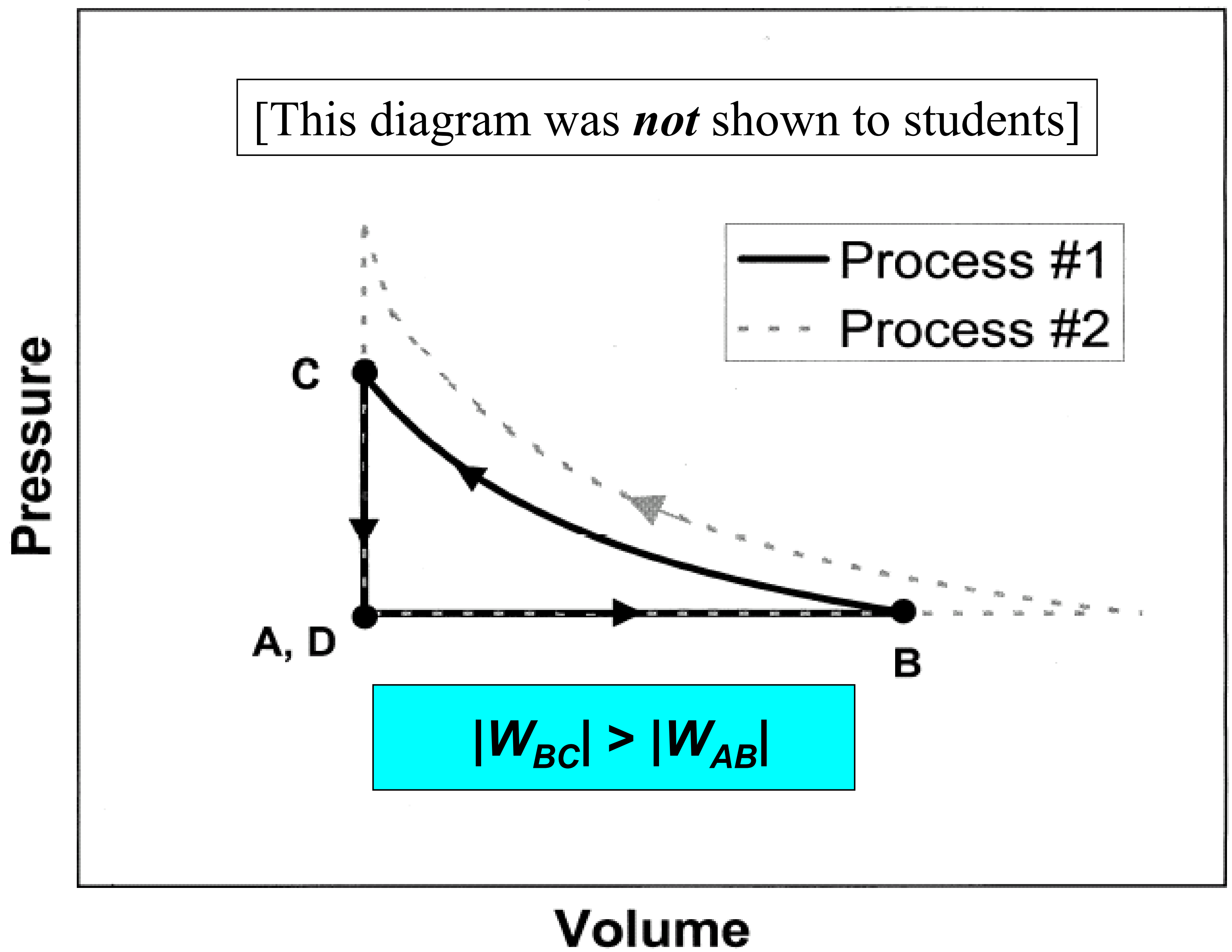
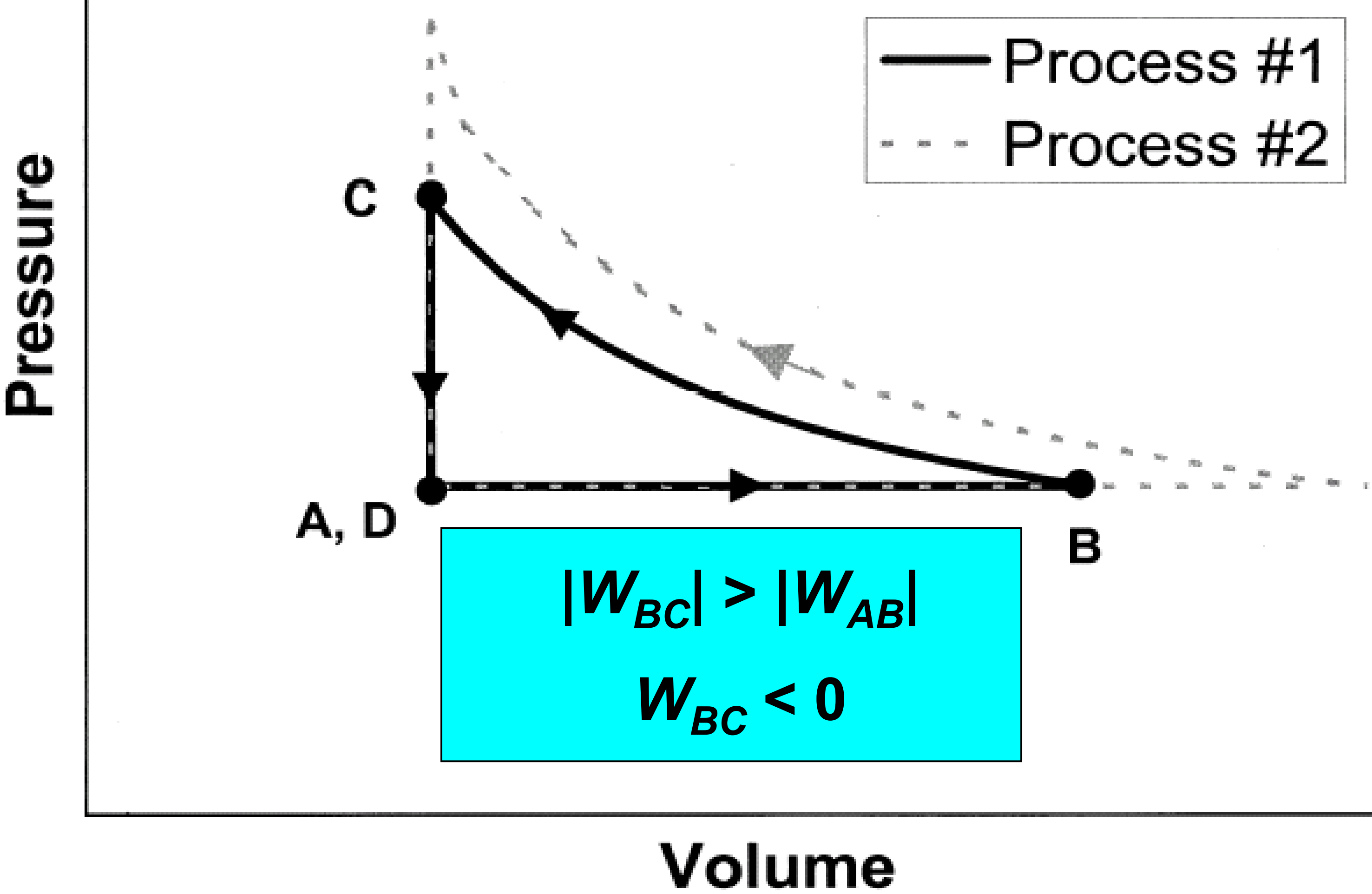
Pressure
Volume

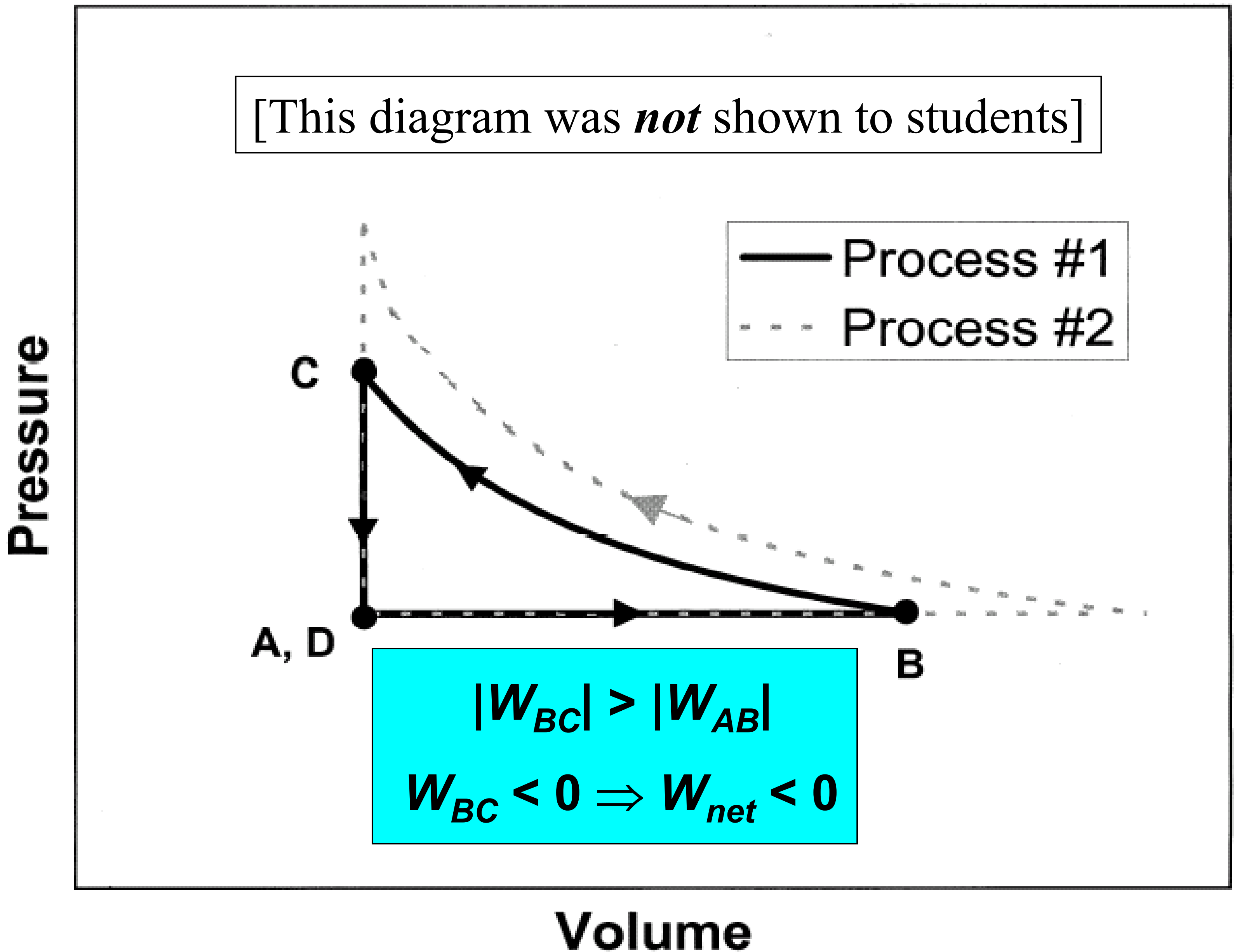

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume
|W_BC| > |W_AB|

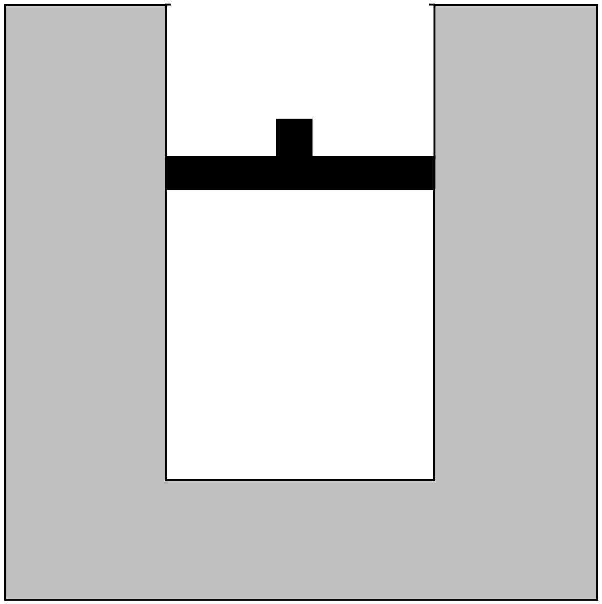
[This diagram was ***not*** shown to students]



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

$W_{BC} < 0$


[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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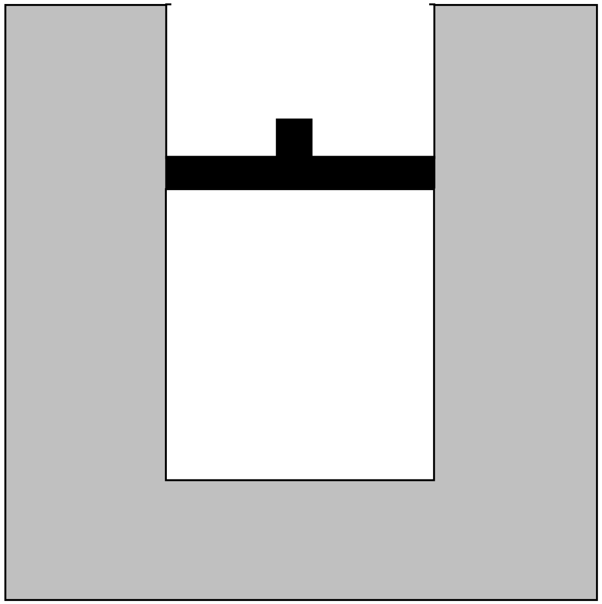

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Results on Interview Question #6 (i)

N = 32

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

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

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

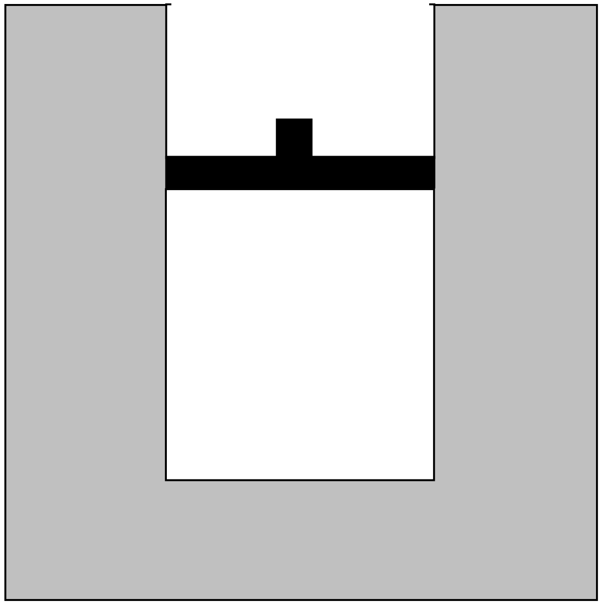
No response: 3%

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*."

"[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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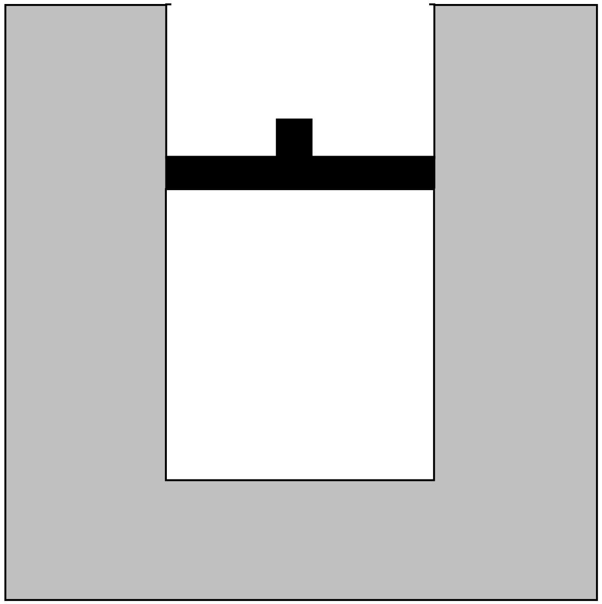

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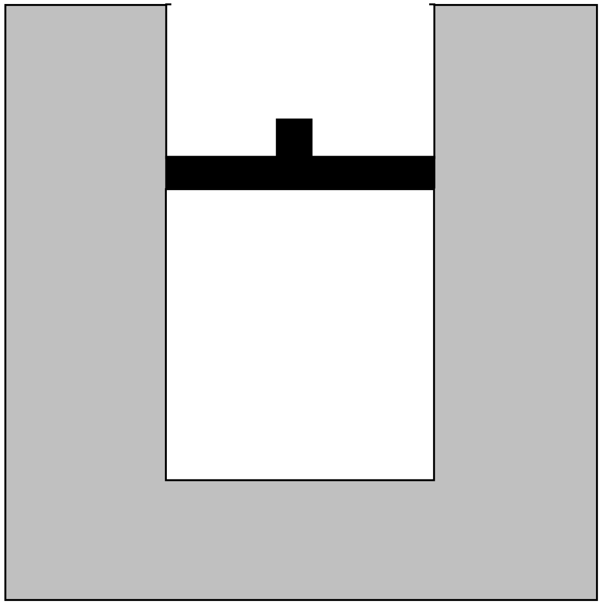

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(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or **(c) less than zero?**

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%**

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

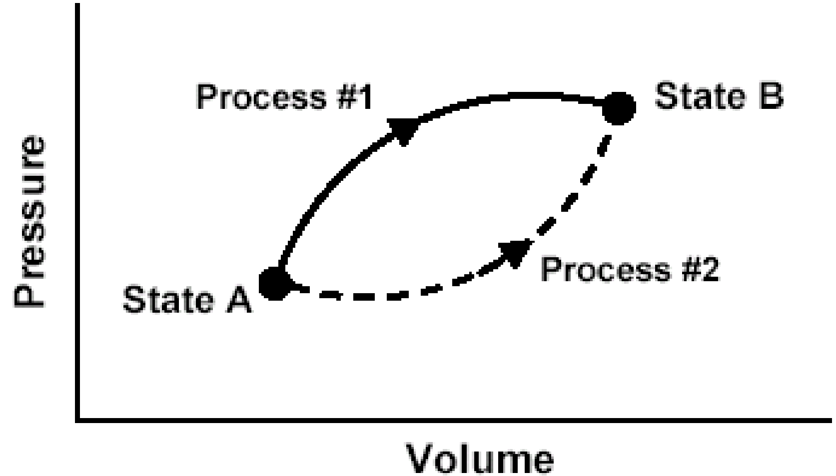
Explanation offered for $Q_{net} = 0$

"*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.*"

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.]

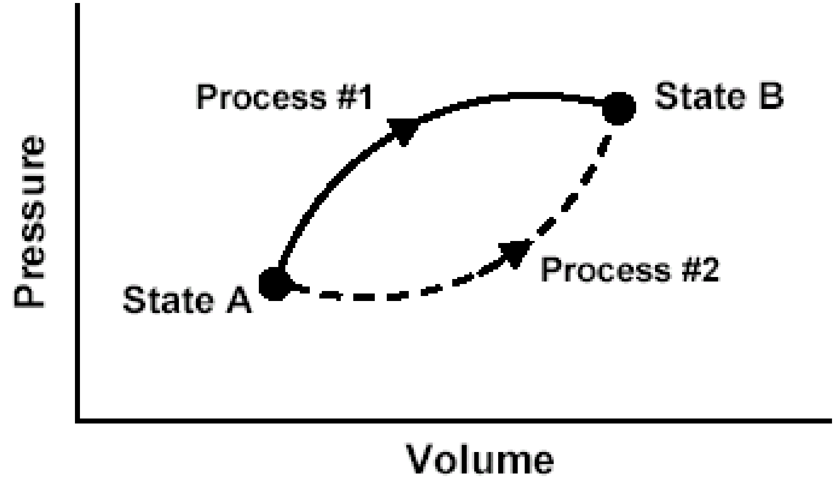
1. Is *W* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2? Explain.

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

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?***

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:

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



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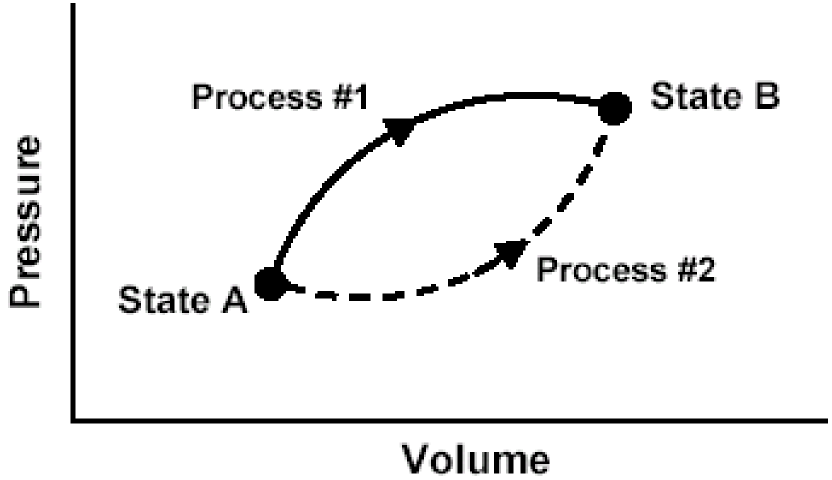
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

The system does more work in Process #1, so it must absorb more heat to reach same final value of internal energy:
$Q_1 > Q_2$



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Responses to Diagnostic Question #2
(Heat question)

	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
$Q_1 > Q_2$ (disregarding explanations)	**56%**	**40%**	**40%**	**34%**

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*."

"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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$Q_1 > Q_2$	**56%**	**40%**	**40%**	**34%**
Correct or partially correct explanation	**14%**	**10%**	**10%**	**19%**

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	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
$Q_1 > Q_2$	**56%**	**40%**	**40%**	**34%**
Correct or partially correct explanation	**14%**	**10%**	**10%**	**19%**
Incorrect, or missing explanation	**42%**	**30%**	**30%**	**15%**

Fewer than 20% of Students are Able to Apply First Law

- Fewer than 20% of students overall could explain why $Q_1 > Q_2$.
- Fewer than 20% of students in interview sample were able to use first law correctly.

➡ **Large majority of students finish general physics course unable to apply first law of thermodynamics.**

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Large majority of students finish general physics course unable to apply first law of thermodynamics.

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

Fewer than 20% of Students are Able to Apply First Law

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- Fewer than 20% of students in interview sample were able to use first law correctly.

→ **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

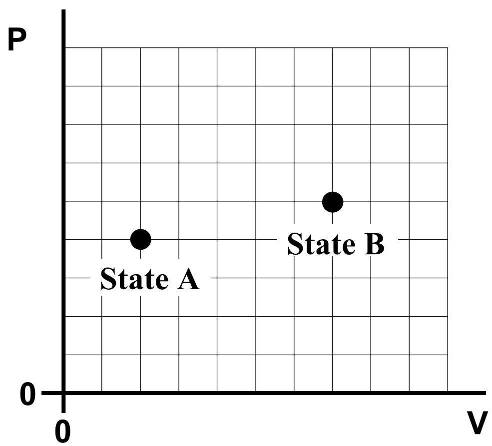
- Certain common idealizations are very troublesome for many students (e.g., the relation between temperature and kinetic energy of an ideal gas; the meaning of thermal reservoir).
- The persistence of these difficulties suggests that it might be useful to guide students to provide their own justifications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

Thermodynamics Worksheet

For an ideal gas, the internal energy U is directly proportional to the temperature T. (This is because the internal energy is just the total kinetic energy of all of the gas molecules, and the temperature is defined to be equal to the *average* molecular kinetic energy.) For a monatomic ideal gas, the relationship is given by $U = \frac{3}{2}nRT$, where n is the number of moles of gas, and R is the universal gas constant.

1. Find a relationship between the internal energy of n moles of ideal gas, and pressure and volume of the gas. Does the relationship change when the number of moles is varied?

2. Suppose that m moles of an ideal gas are contained inside a cylinder with a movable piston (so the volume can vary). At some initial time, the gas is in state A as shown on the PV-diagram in Figure 1. A thermodynamic process is carried out and the gas eventually ends up in State B. Is the internal energy of the gas in State B *greater than*, *less than*, or *equal to* its internal energy in State A? (That is, how does U_B compare to U_A?) Explain.

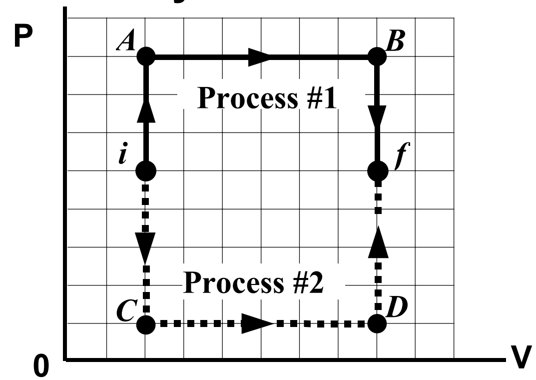


3. If a system starts with an initial internal energy of $U_{initial}$ and ends up with U_{final} some time later, we symbolize the *change* in the system's internal energy by ΔU and define it as follows: $\Delta U = U_{final} - U_{initial}$.

   a. For the process described in #2 (where the system goes from State A to State B), is ΔU for the gas system *greater than zero*, *equal to zero*, or *less than zero*?

   b. During this process, was there any energy transfer between the gas system and its surrounding environment? Explain.

Thermodynamics Worksheet



7. Rank the *temperature* of the gas at the six points *i*, *A*, *B*, *C*, *D*, and *f*. (Remember this is an *ideal* gas.)

8. Consider all sub-processes represented by straight-line segments. For each one, state whether the work is positive, negative, or zero. In the second column, rank all six processes according to their ΔU. (Pay attention to the sign of ΔU.) If two segments have the same ΔU, give them the same rank. In the last column, state whether heat is added *to* the gas, taken *away* from the gas, or is *zero* (i.e., *no* heat transfer). ***Hint:*** **First determine *U* for each point using the result of #1 on page 1.**

Process	**Is *W* +, –, or 0?**	**rank according to ΔU**	**heat added *to*, taken *away*, or *zero*?**
$i \rightarrow A$			
$A \rightarrow B$			
$B \rightarrow f$			
$i \rightarrow C$			
$C \rightarrow D$			
$D \rightarrow f$			

9. Consider **only** the sub-processes that have $W = 0$. Of these, which has the *greatest* absolute value of heat transfer *Q*? Which has the *smallest* absolute value of *Q*?

10. Rank the six segments in the table above according to the absolute value of their *W*. *Hint:* For processes at constant pressure, $W = P\,\Delta V$.

11. Using your answers to #8 and #10, explain whether W_1 is *greater than*, *less than*, or *equal to* W_2. [Refer to definitions, page 3.] Is there also a way to answer this question using an "area" argument?

12. Is Q_1 *greater than*, *less than*, or *equal to* Q_2? Explain. *Hint:* Compare the magnitude of ΔU_1 and ΔU_2, and make use of the answer to #6.

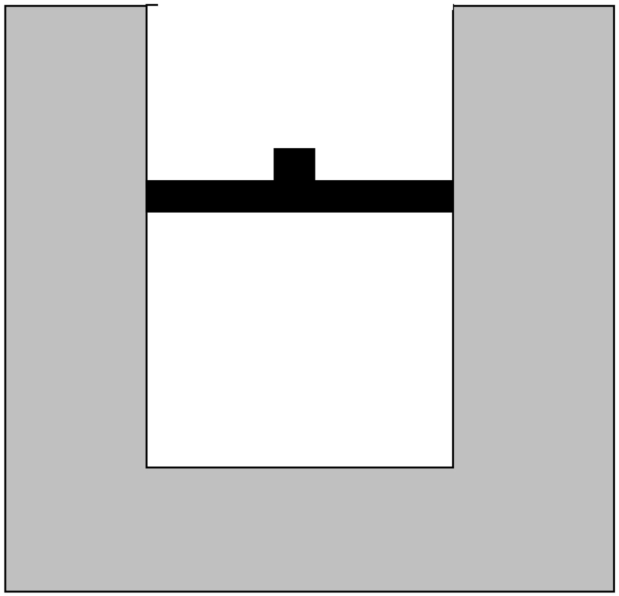
Implementation of Instructional Model

"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

Cyclic Process Worksheet

(adapted from interview questions)

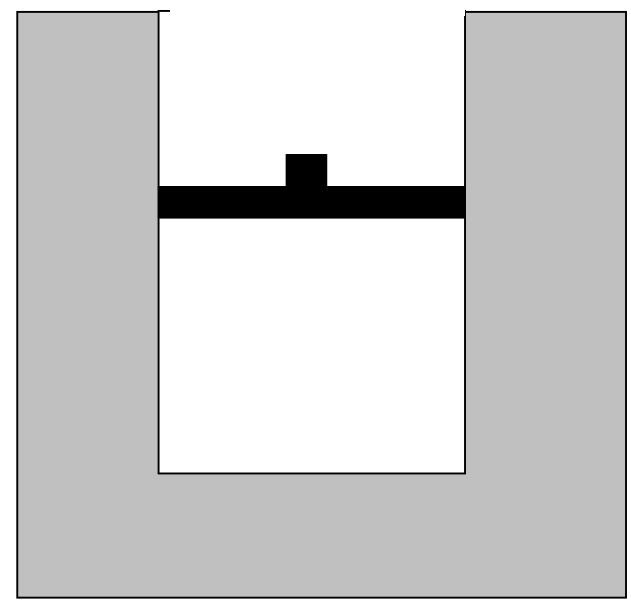


Worksheet Strategy

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

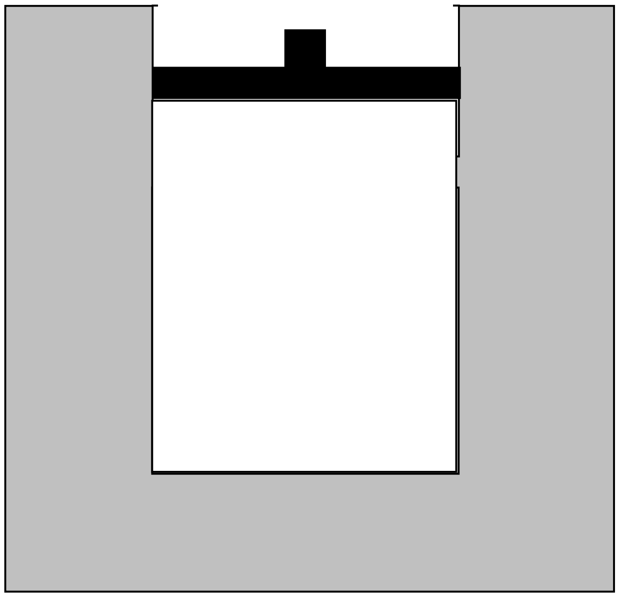
Time *A*

System heated

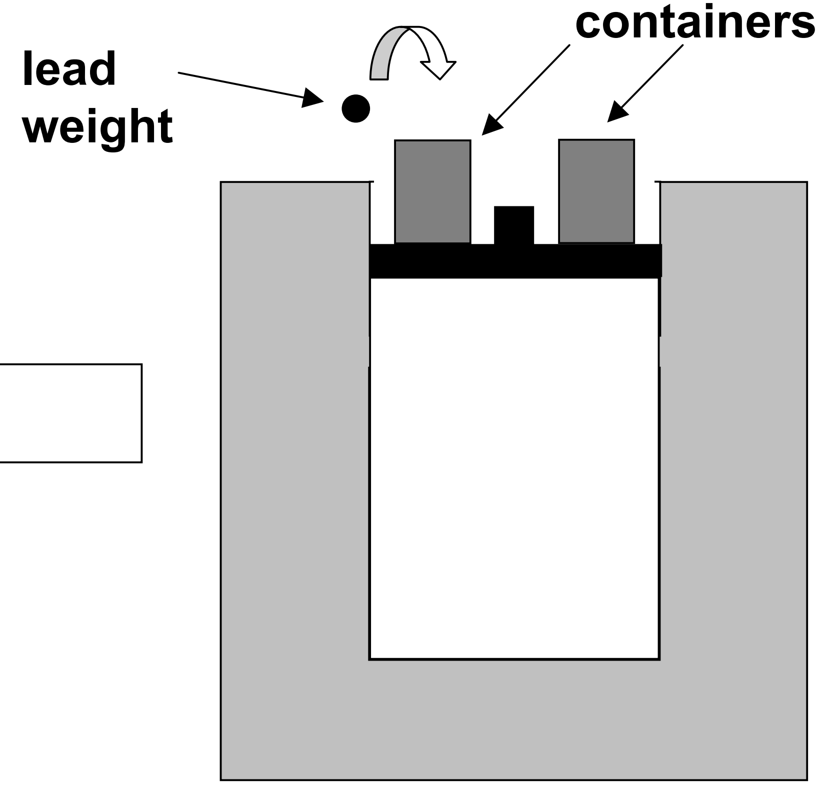


Time *B*

System heated, piston goes up.



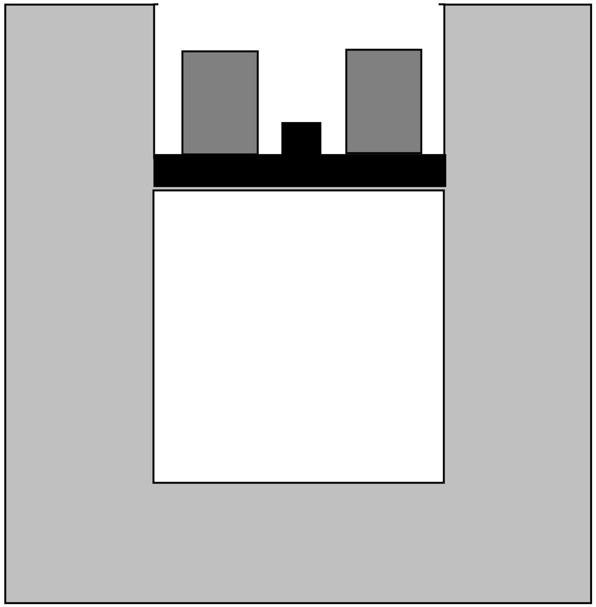
Time *B*



Weights added

Time *C*

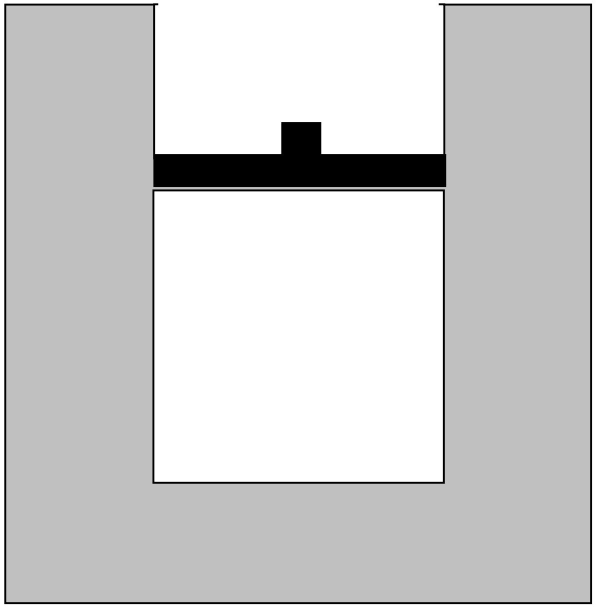
Weights added, piston goes down.



Time *C*

Temperature *C*

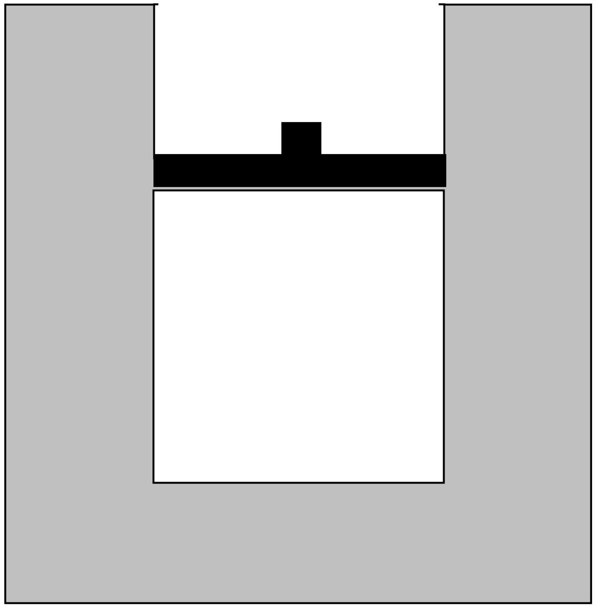
Piston locked

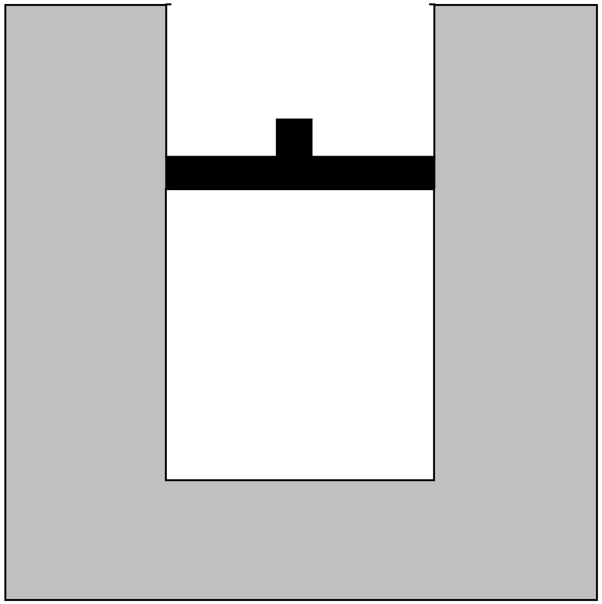


Time *D*

Temperature *D*

Piston locked, temperature goes down.





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

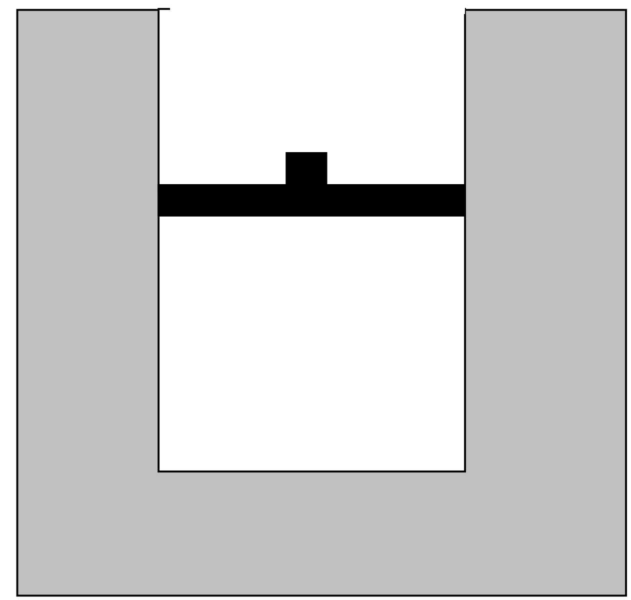
(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

(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?

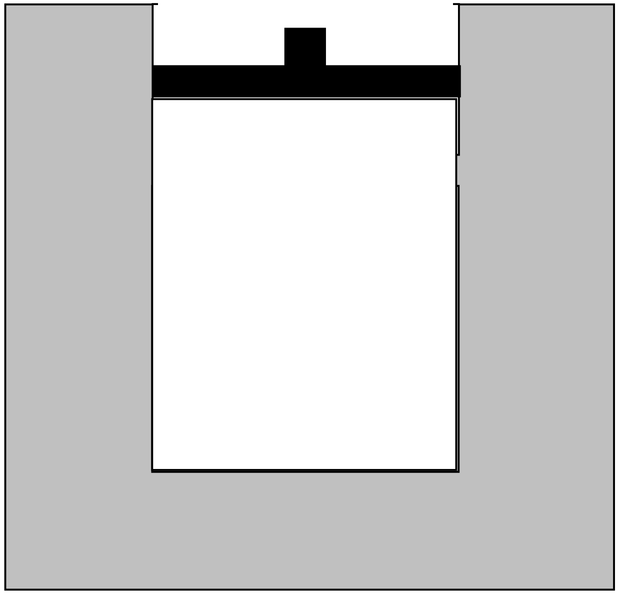
Worksheet Strategy

- 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*



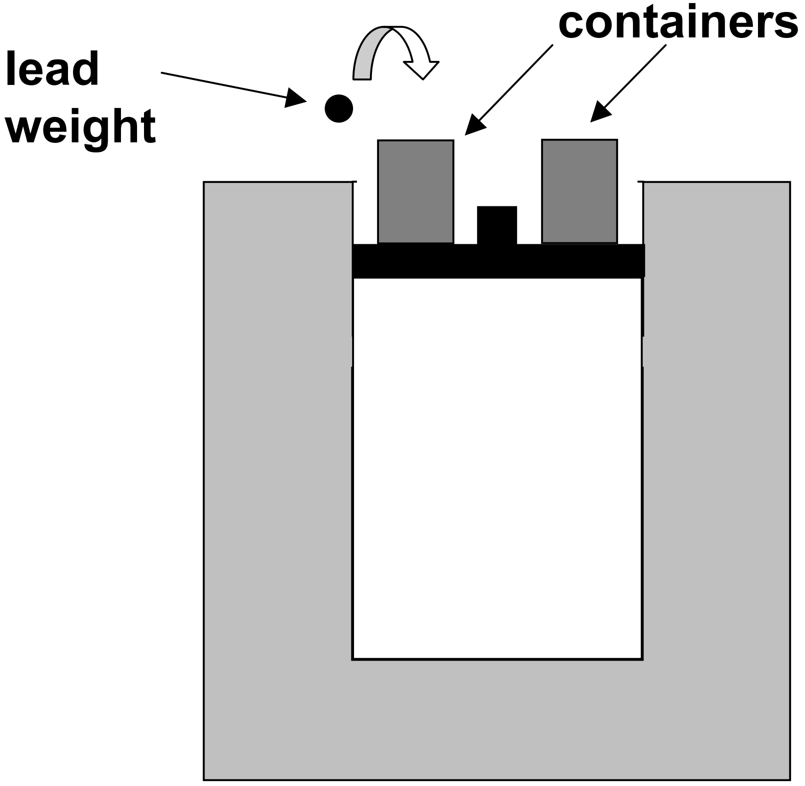
Time *B*



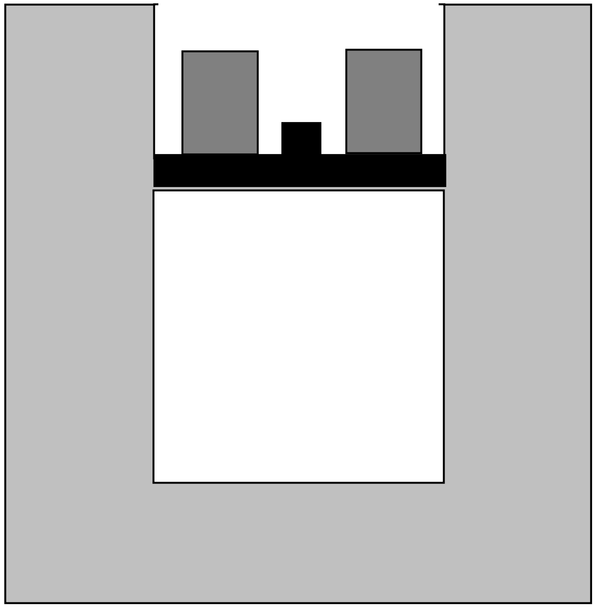
1) For the process A → B, is the work done by the system (W_{AB}) *positive*, *negative*, or *zero*?

Explain your answer.

Time *B*



Time *C*

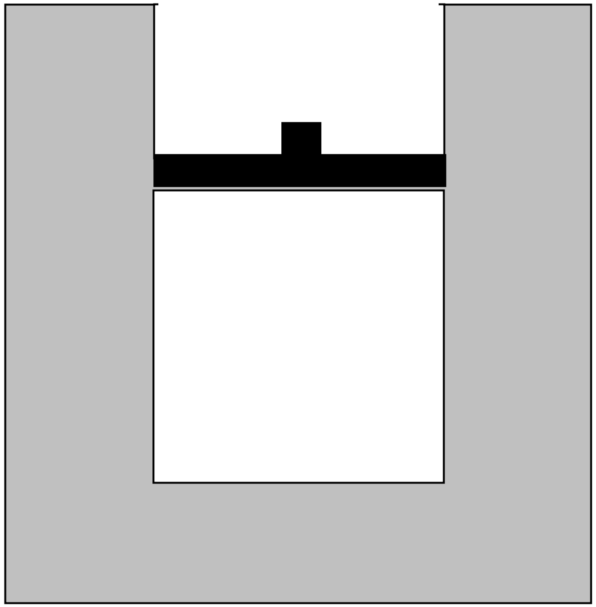


1) For the process A → B, is the work done by the system (W_{AB}) *positive*, *negative*, or *zero*?

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

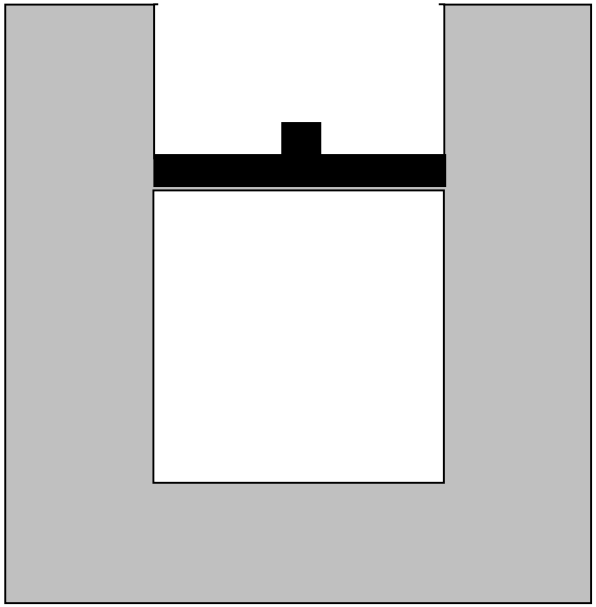
Time *C*

Temperature *C*



Time *D*

Temperature *D*



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*?

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.

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

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

$$W_{\text{net}} = W_{\text{AB}} + W_{\text{BC}} + W_{\text{CD}}$$

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

$$W_{net} = W_{AB} + W_{BC} + W_{CD}$$

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

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

$$W_{net} = W_{AB} + W_{BC} + W_{CD}$$

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.

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

$$W_{net} = W_{AB} + W_{BC} + W_{CD}$$

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.

Thermodynamics Curricular Materials

- Preliminary versions and initial testing of worksheets for:
  - calorimetry
  - thermochemistry
  - first-law of thermodynamics
  - cyclic processes
  - Carnot cycle
  - entropy
  - free energy

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Preliminary testing in general physics and in junior-level thermal physics course

Summary

- Difficulties with fundamental concepts and common idealizations 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.
- Further research is necessary on more advanced topics to investigate students' reasoning and develop more effective learning strategies.