Students' Reasoning Regarding Heat, Work, and the First Law of Thermodynamics

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Introduction

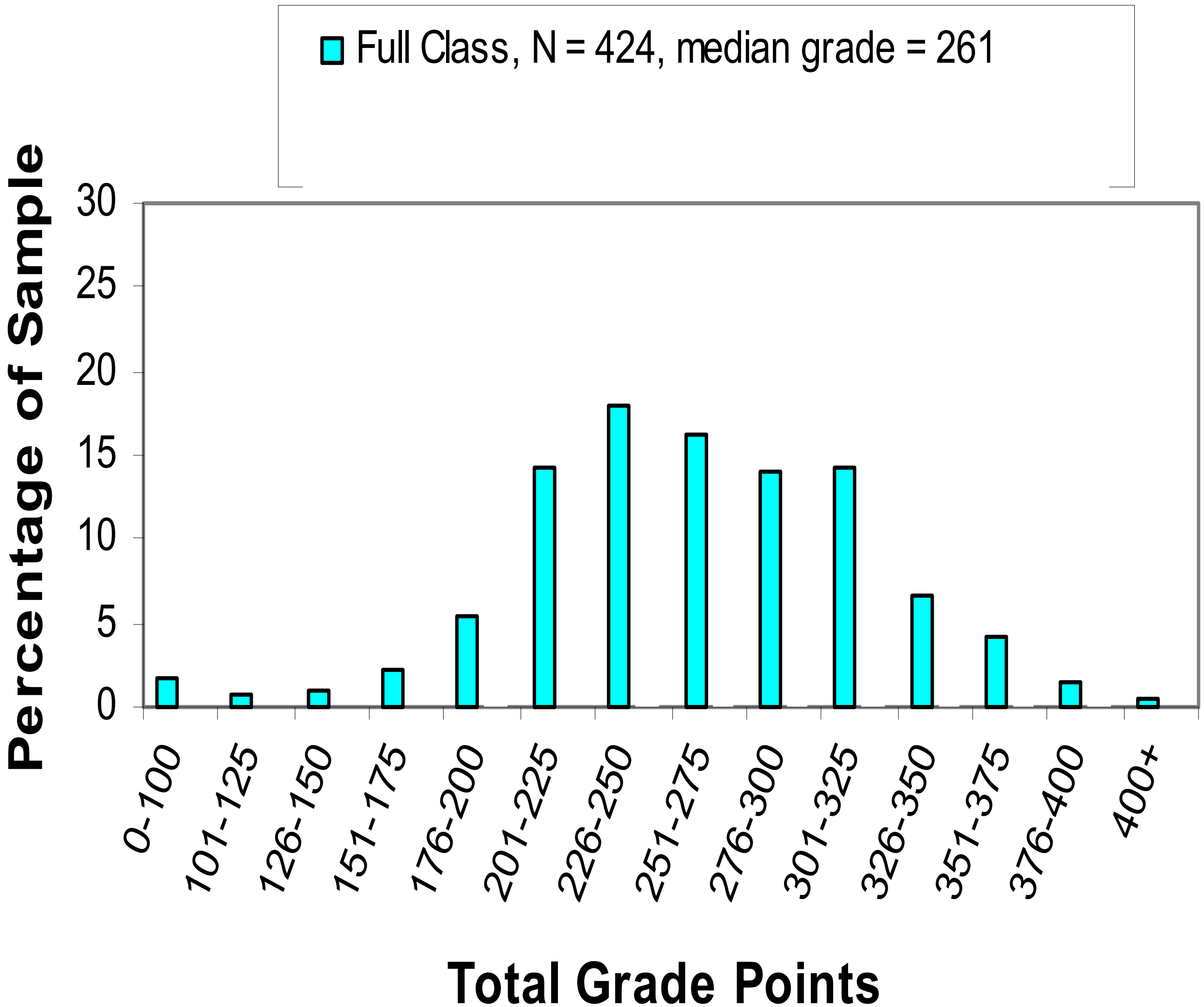
- There have been more than 200 investigations of pre-college students' learning of thermodynamics concepts, all showing serious conceptual difficulties.
- Recently published study of university students showed substantial difficulty with work concept and with the first law of thermodynamics. *M.E. Loverude, 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*

[two course instructors, ≈ 20 recitation instructors]

Grade Distributions: Interview Sample vs. Full Class



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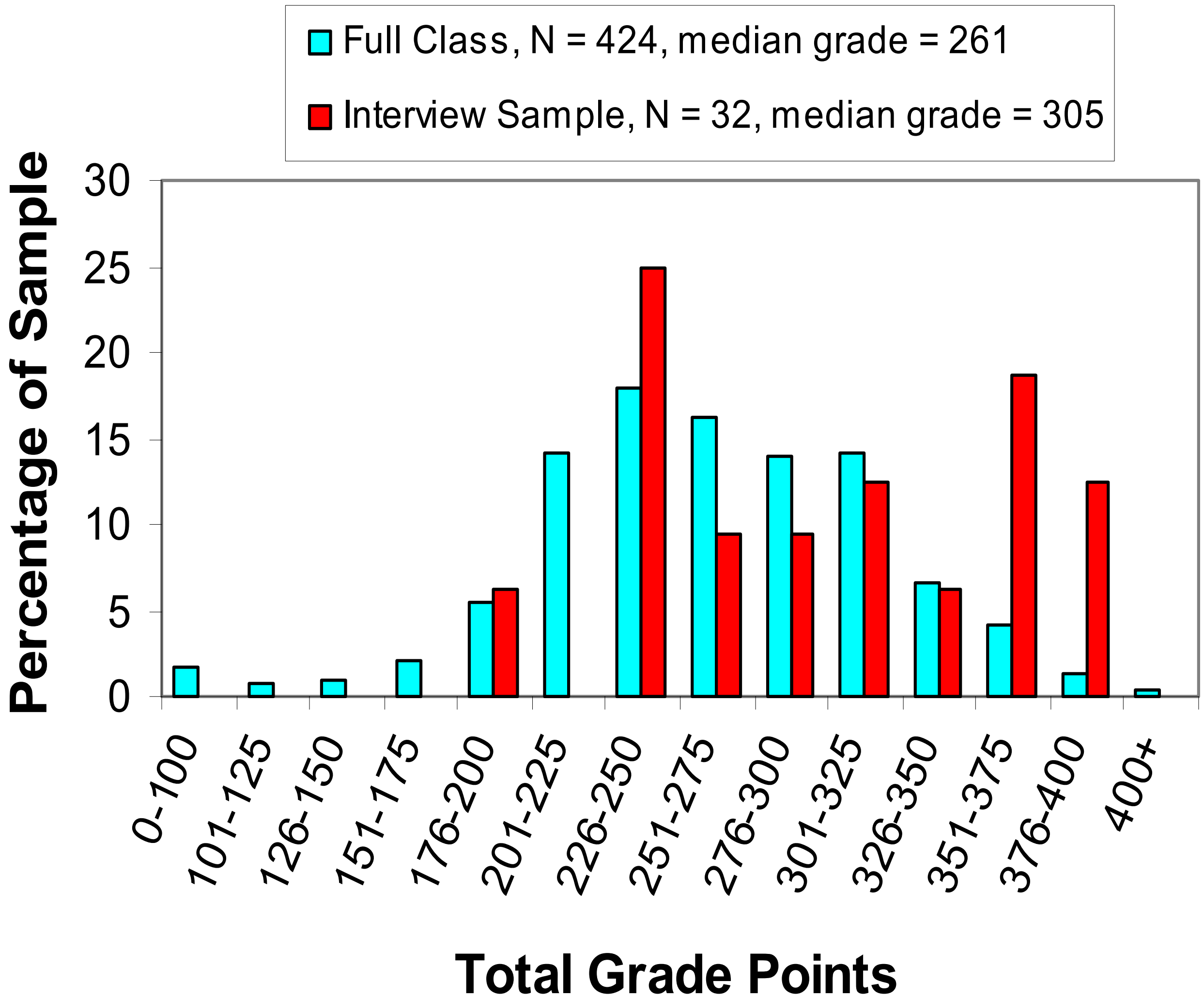

***Interview Sample*:**
34% above 91st percentile; 50% above 81st percentile

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. Failure to recognize "work" as a mechanism of energy transfer.
5. Confusion regarding isothermal processes and the thermal "reservoir."
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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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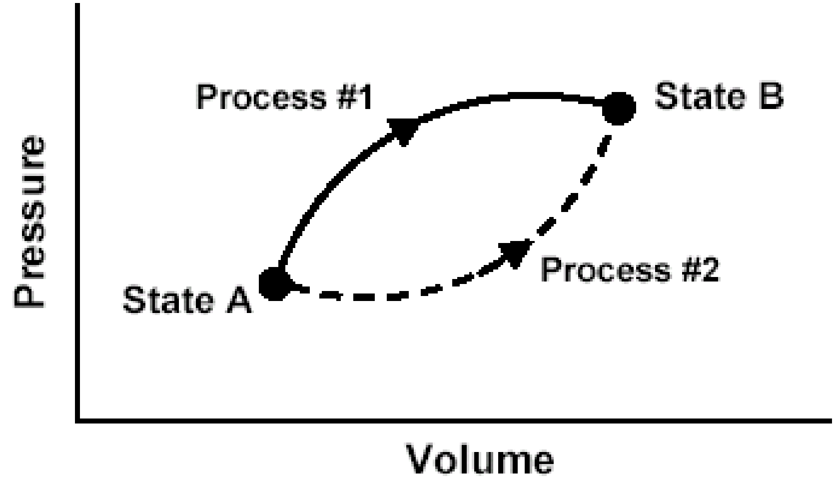

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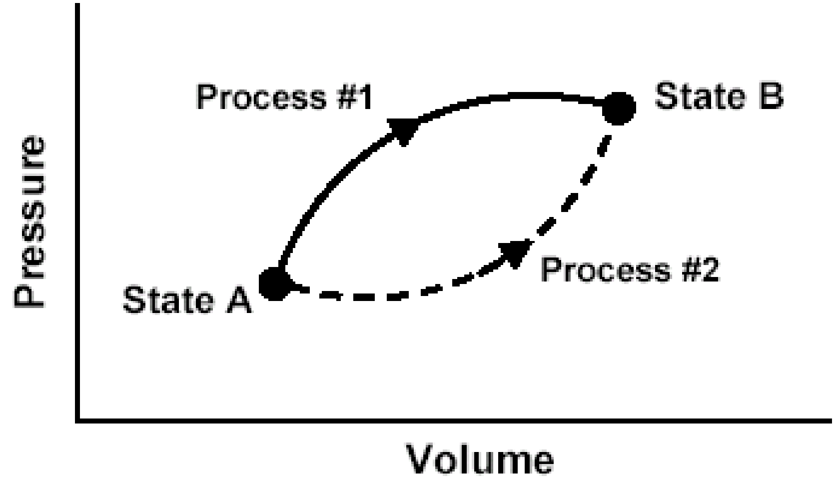

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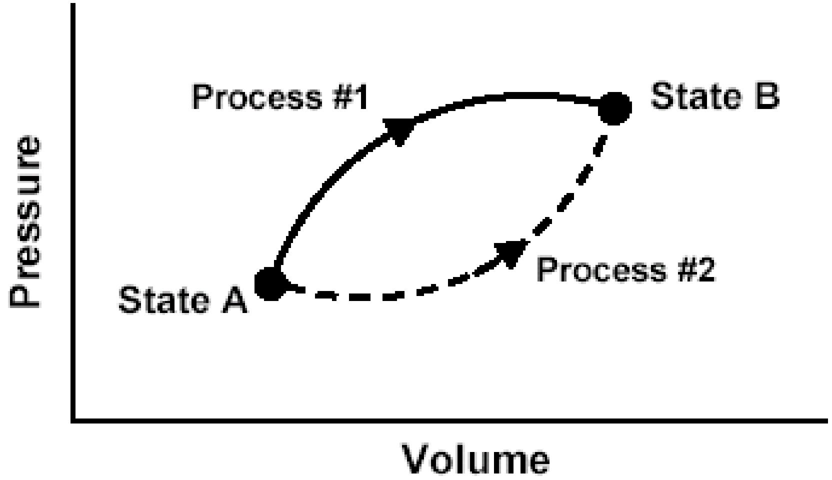

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Students seem to have adequate grasp of state-function concept

- Consistently high percentage (70-90%) of correct responses on relevant questions, 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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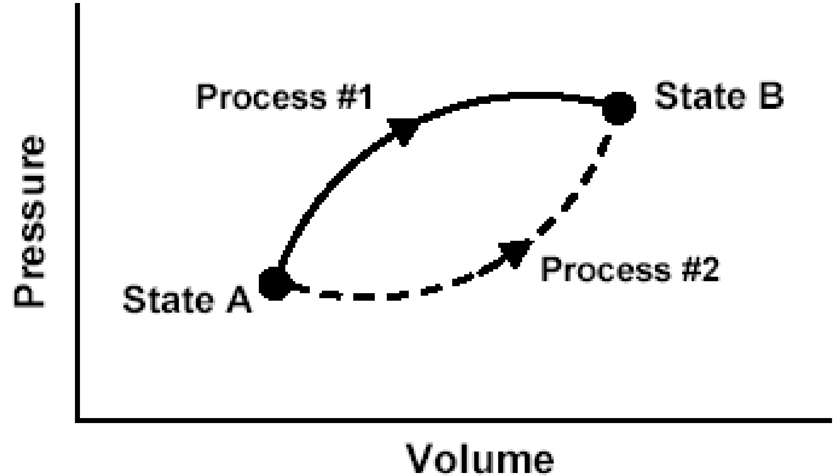

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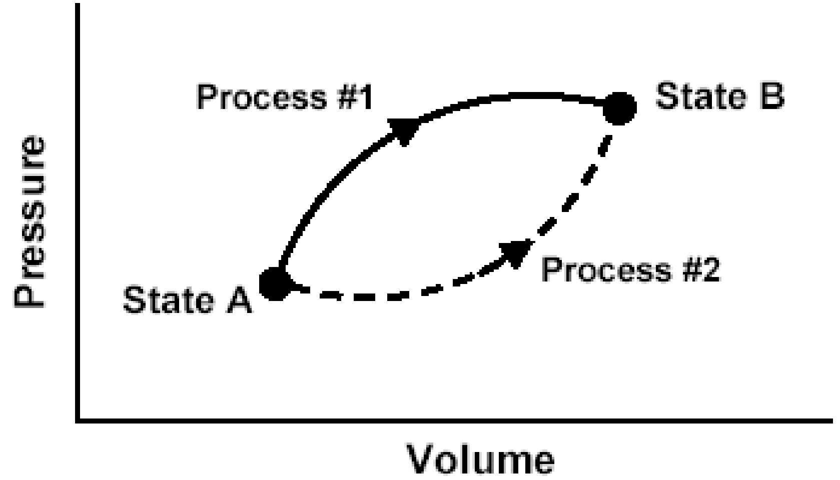

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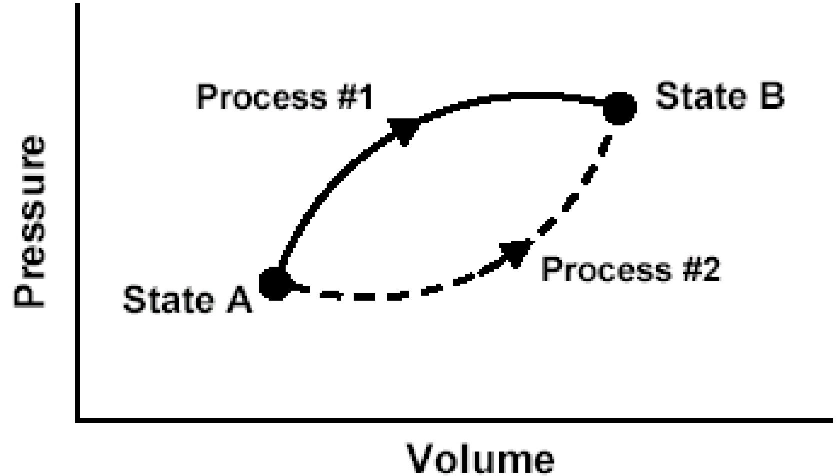

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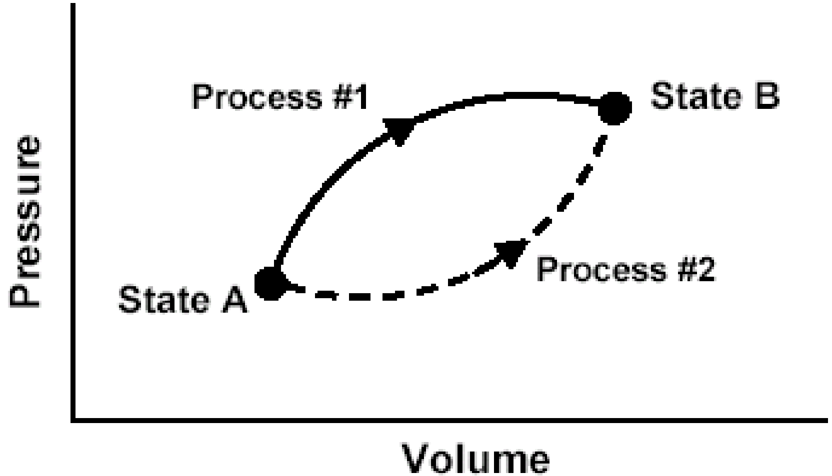

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Responses to Diagnostic Question #1
(Work question)

	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
$W_1 = W_2$	**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.

Confusion with mechanical work done by conservative forces?

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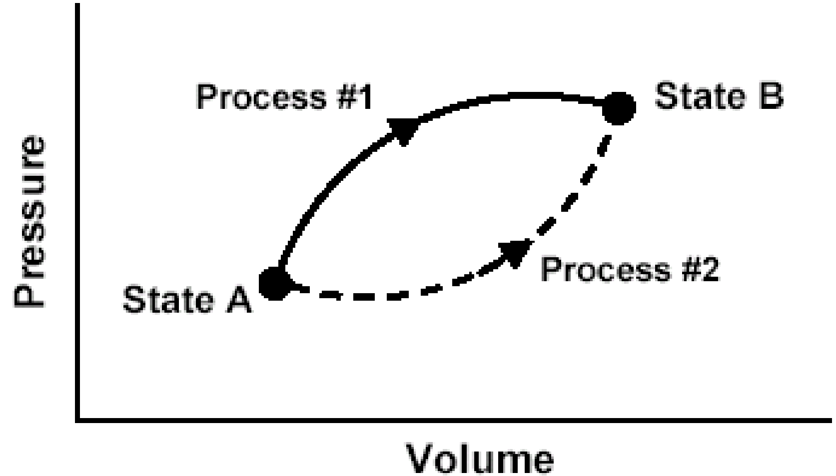

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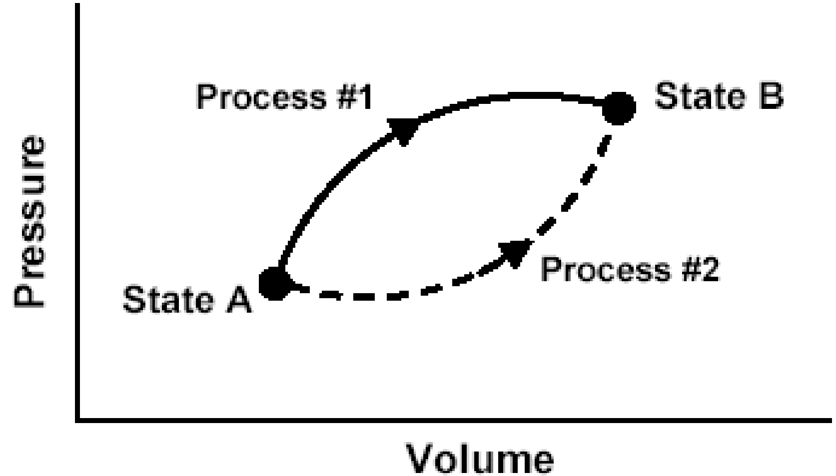
Change in internal energy is the same for Process #1 and Process #2.



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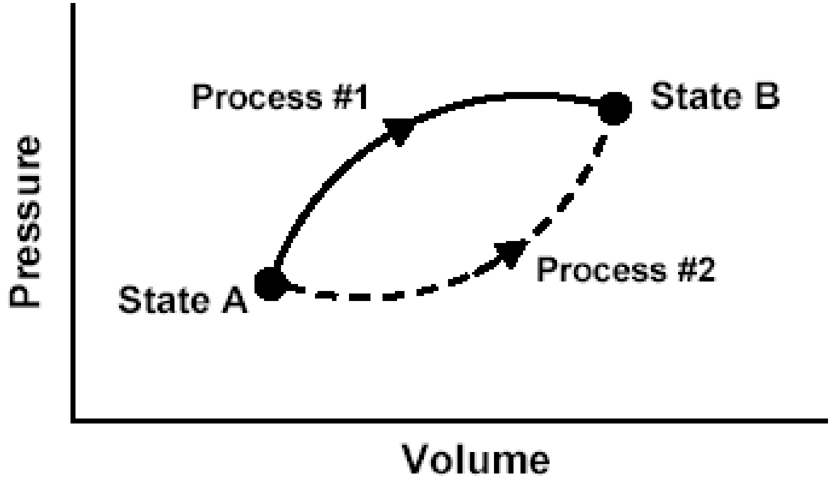
The system does more work in Process #1, so it must absorb more heat to reach same final value of internal energy: $Q_1 > Q_2$



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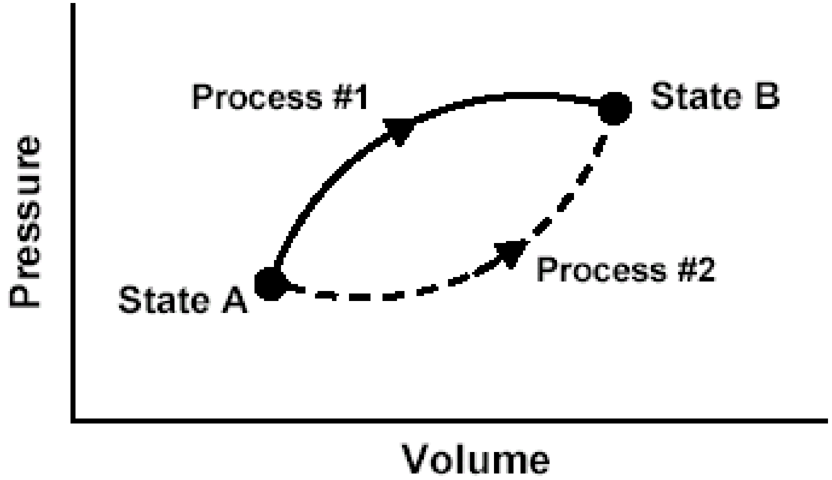
Algebraic Method:

$$\Delta U_1 = \Delta U_2$$

$$Q_1 - W_1 = Q_2 - W_2$$

$$W_1 - W_2 = Q_1 - Q_2$$

$$W_1 > W_2 \Rightarrow Q_1 > Q_2$$



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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)
$Q_1 = Q_2$	**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. Confusion with "$Q = mc\Delta T$" ?**

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

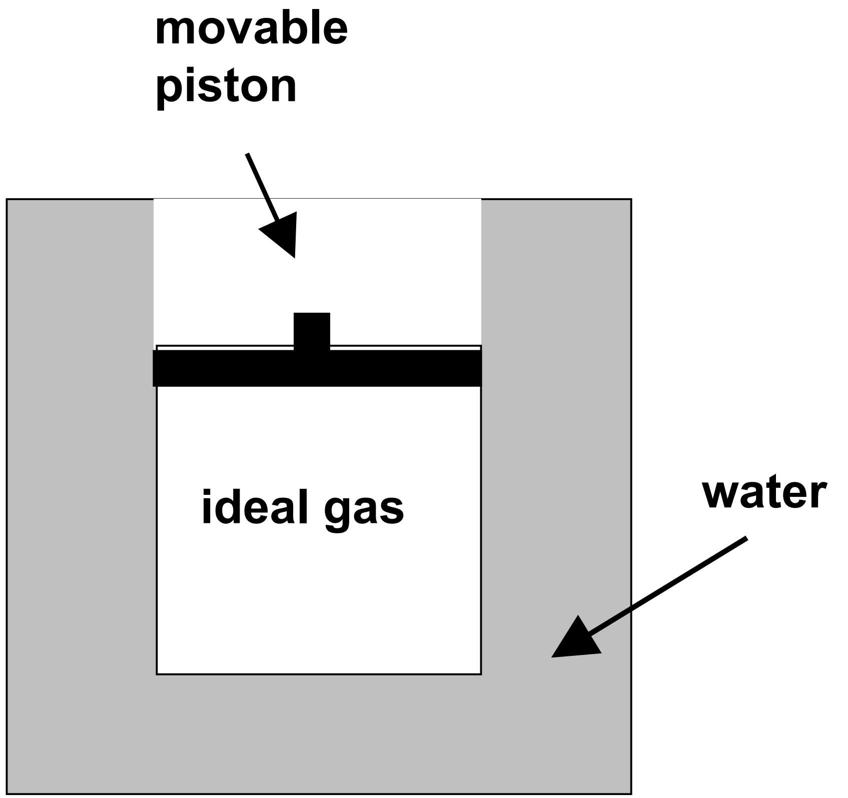
- Basic notion of thermodynamics: if part or all of system boundary is displaced during quasistatic process, energy is transferred between system and surroundings in the form of “work.”
- Study of Loverude, Kautz, and Heron (2002) showed that few students could spontaneously invoke concept of work in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

Interview Questions

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

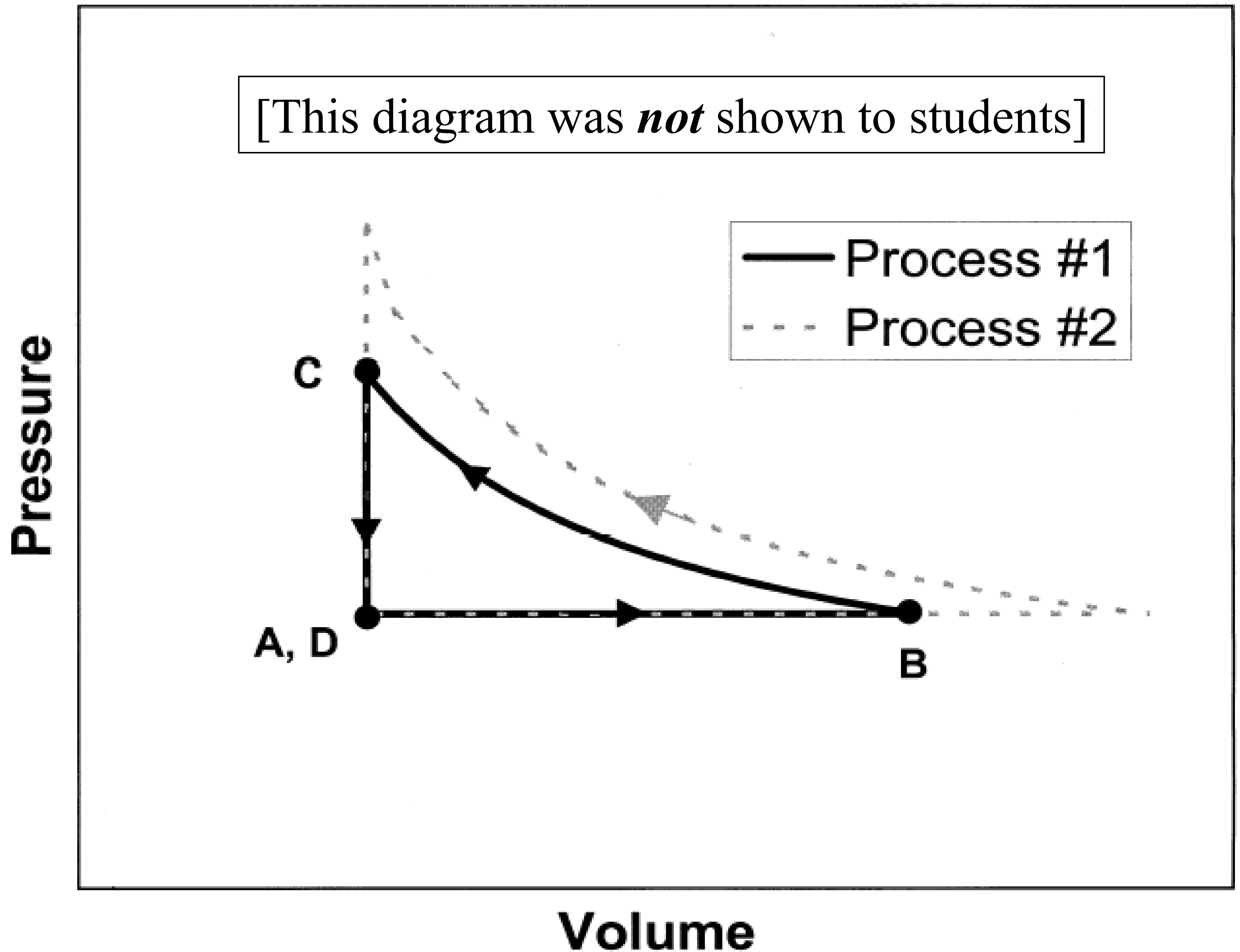
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

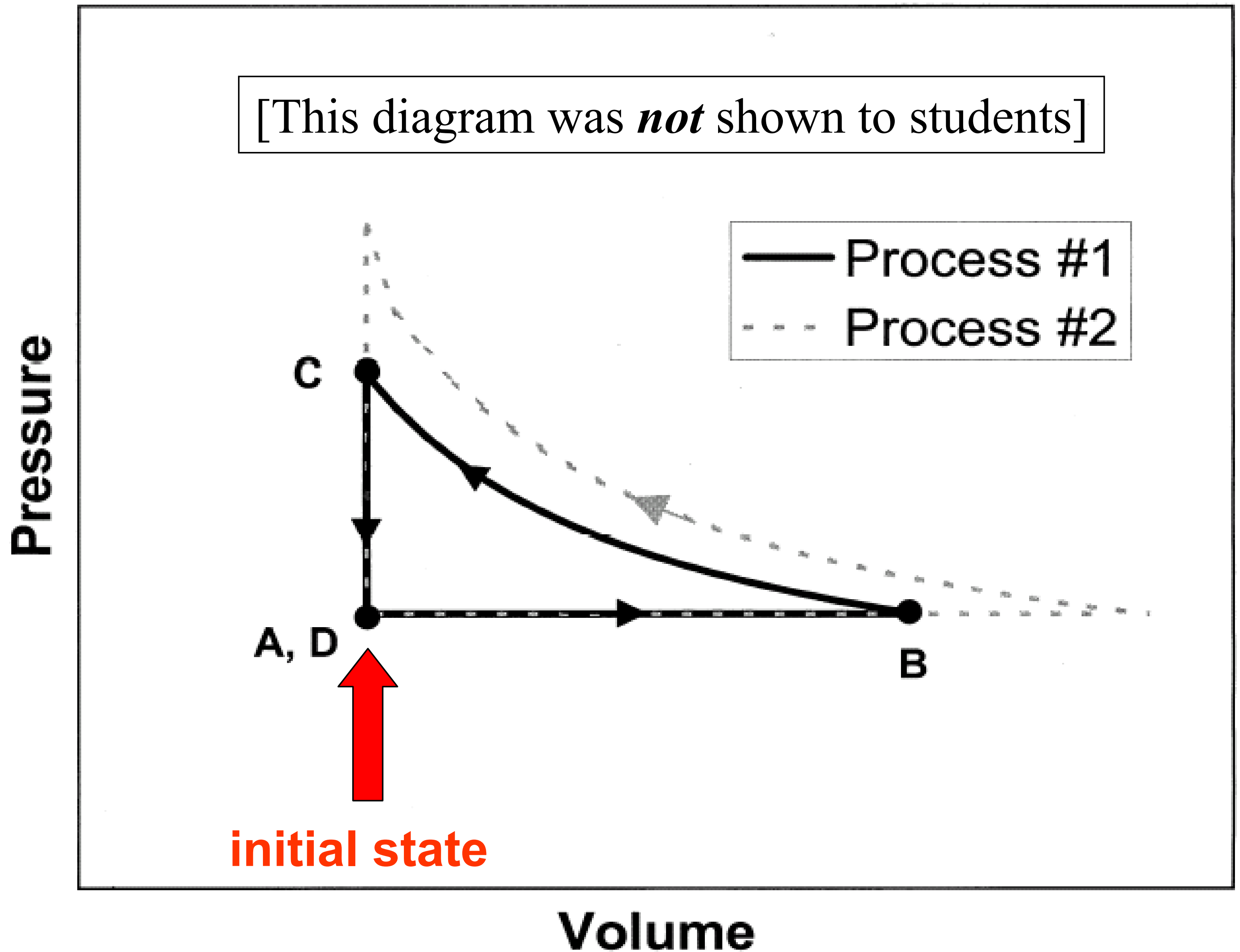
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature



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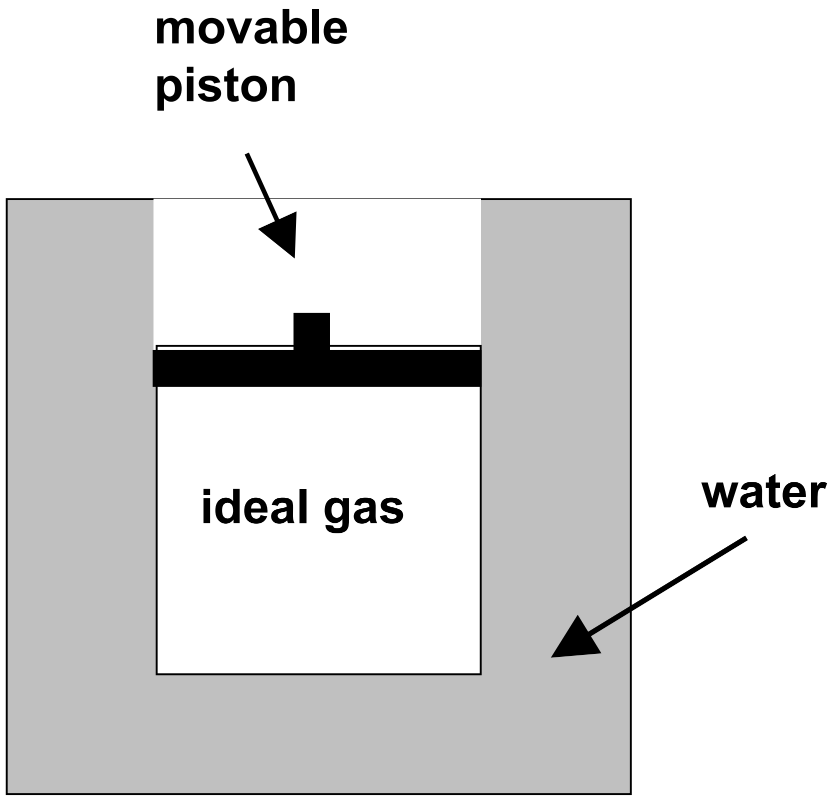
Process #1
Process #2
C
A, D
B
initial state
Pressure
Volume

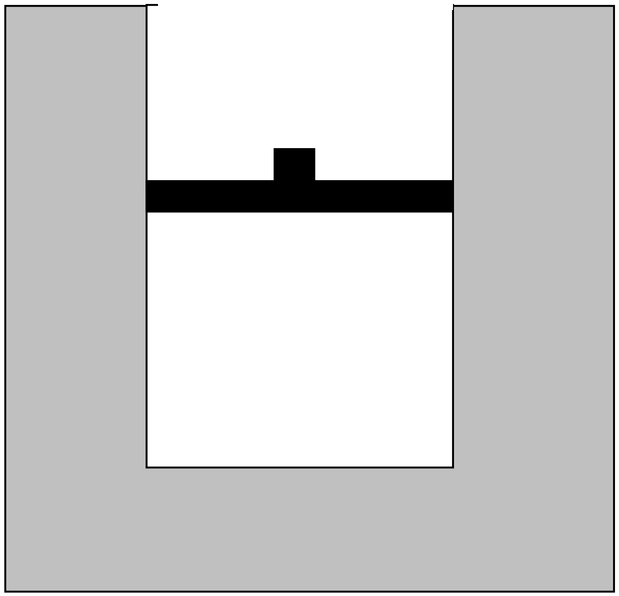
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature

Time *A*

Entire system at room temperature.



Step 1. We now begin Process #1: 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 when it is in the position shown in the diagram below:



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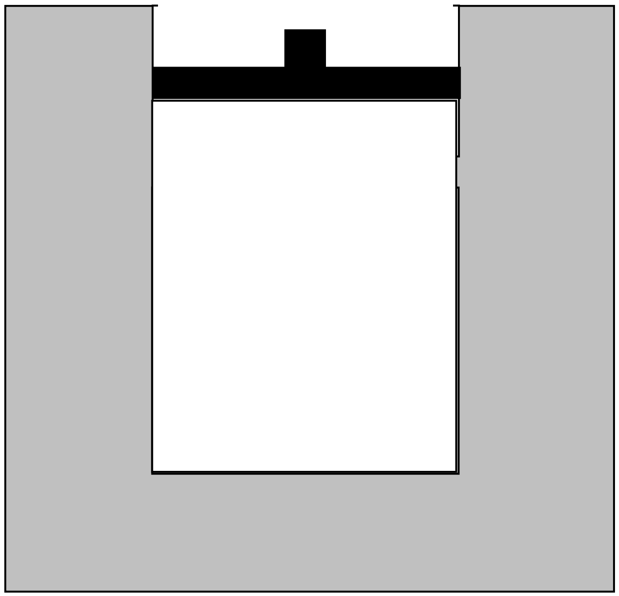

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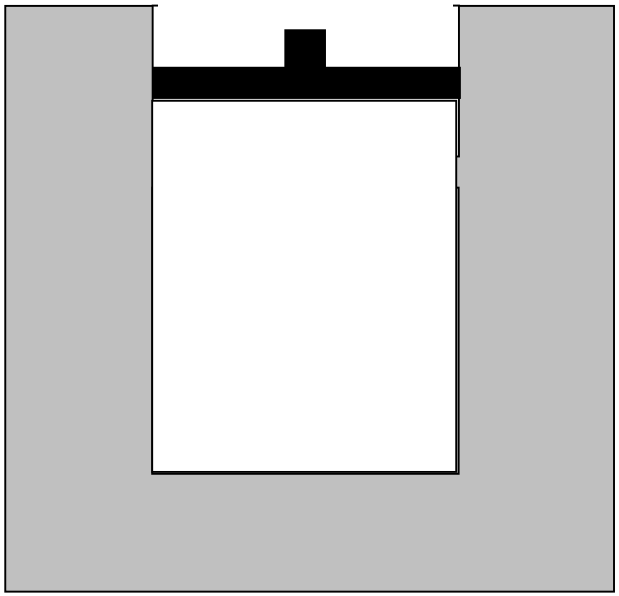
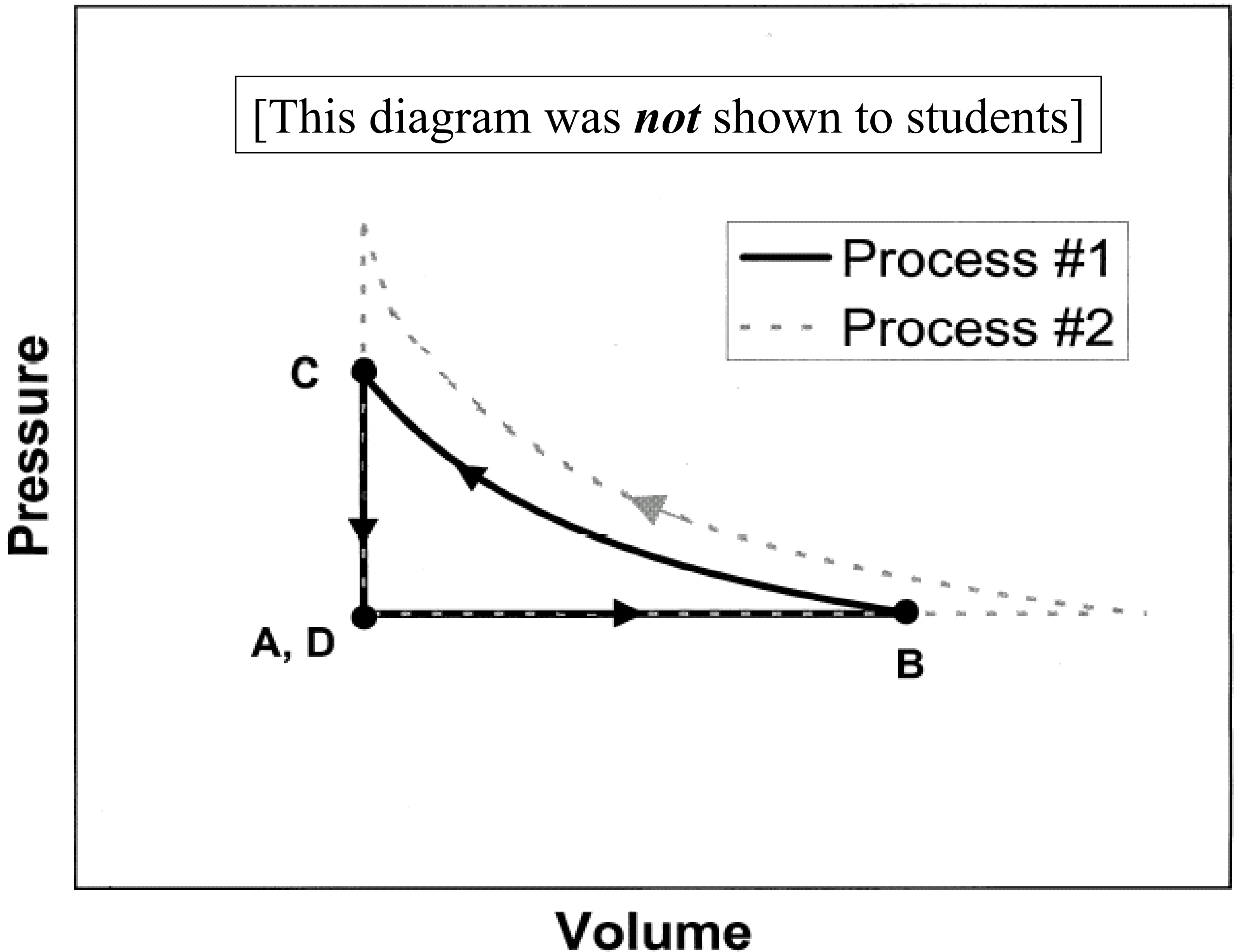
Time *B*

Piston in new position.

Temperature of system has changed.

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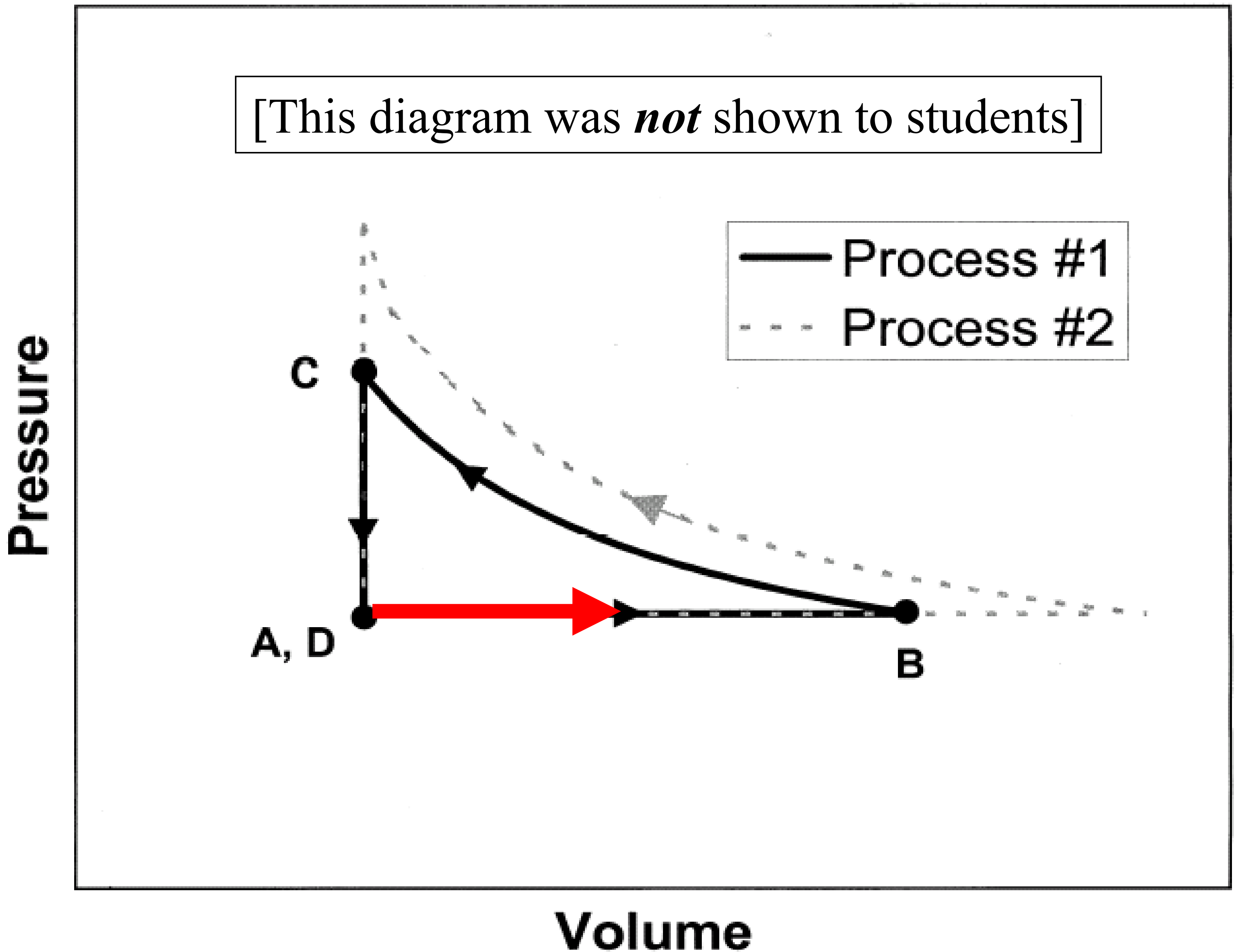

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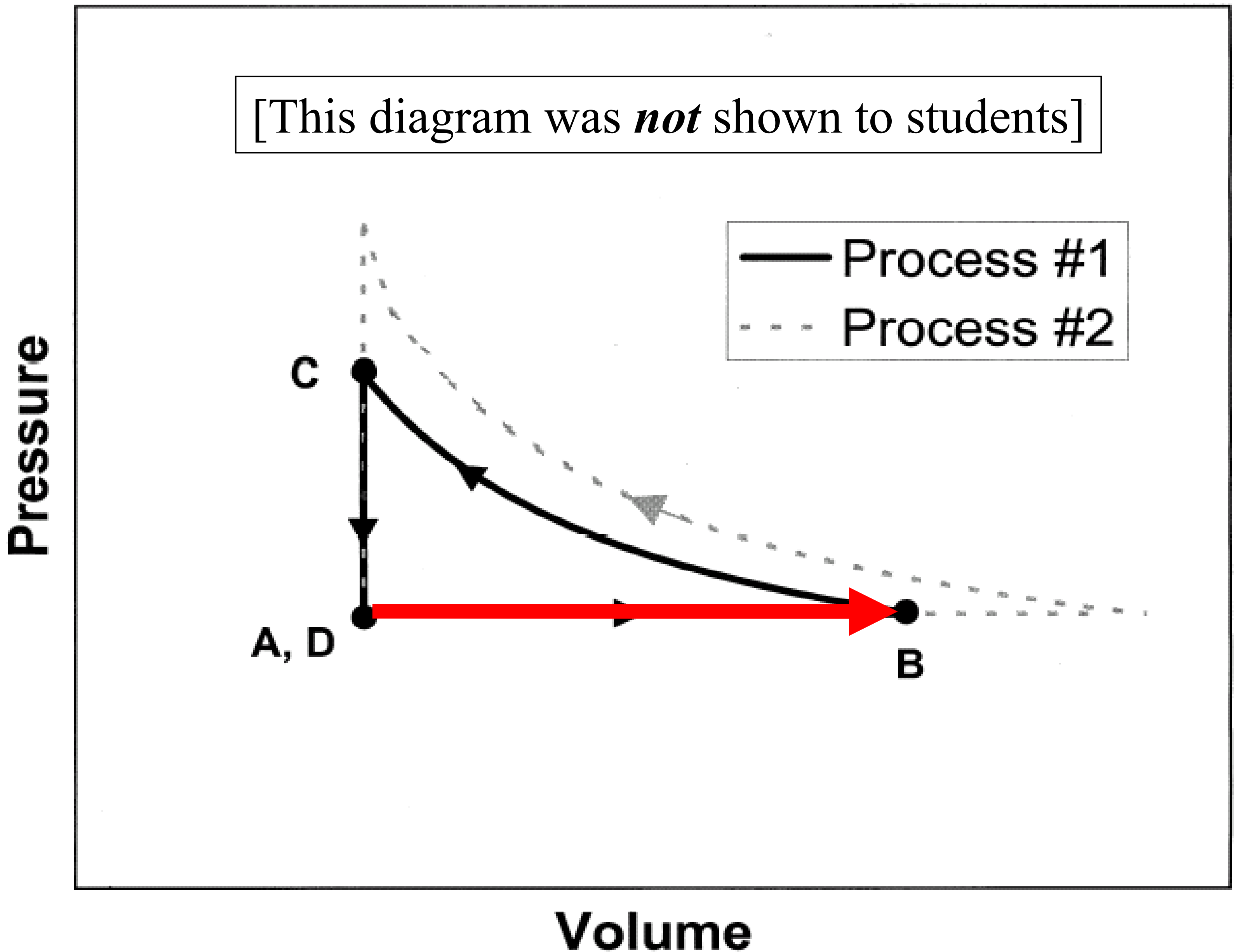
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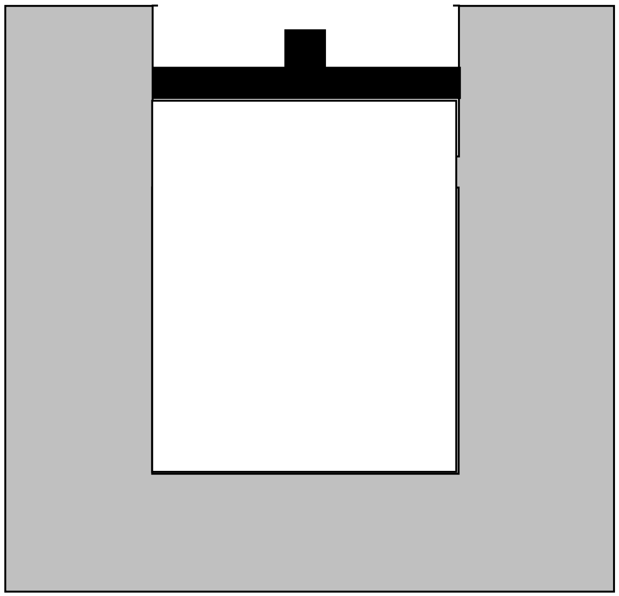

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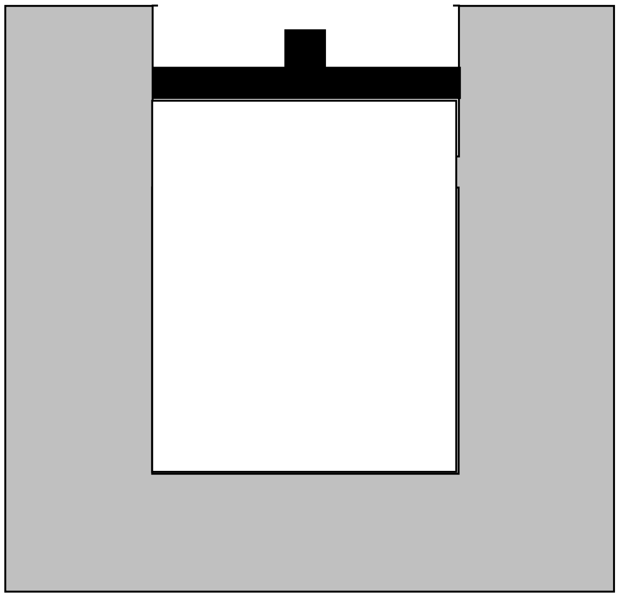

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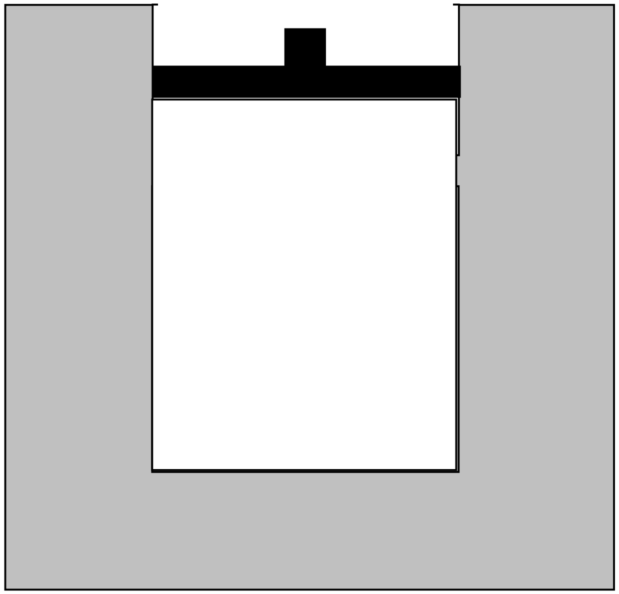

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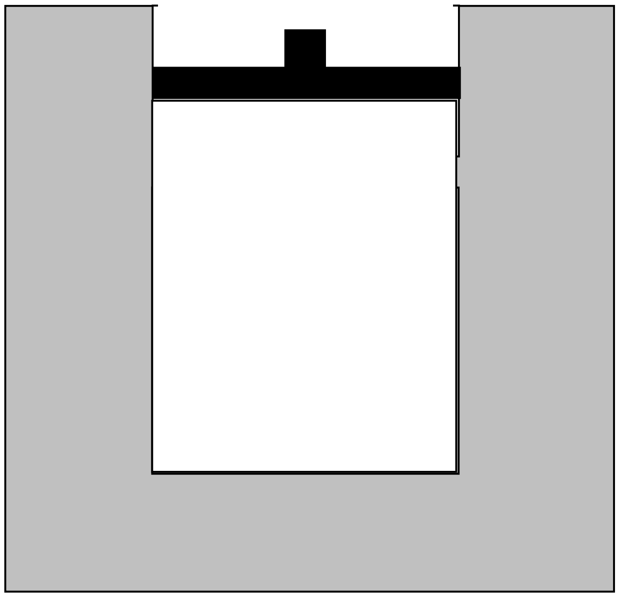

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Results on Question #1

(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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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."

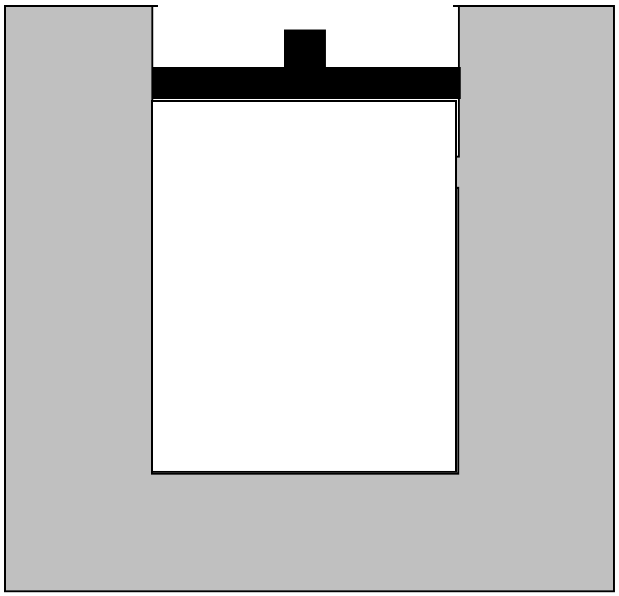
→ *Nearly one third of the interview sample believe that environment does positive work* **on** *gas during expansion.*

Step 1. We now begin Process #1: 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 when it is in the position shown in the diagram below:

Time *B*

Piston in new position.

Temperature of system has changed.



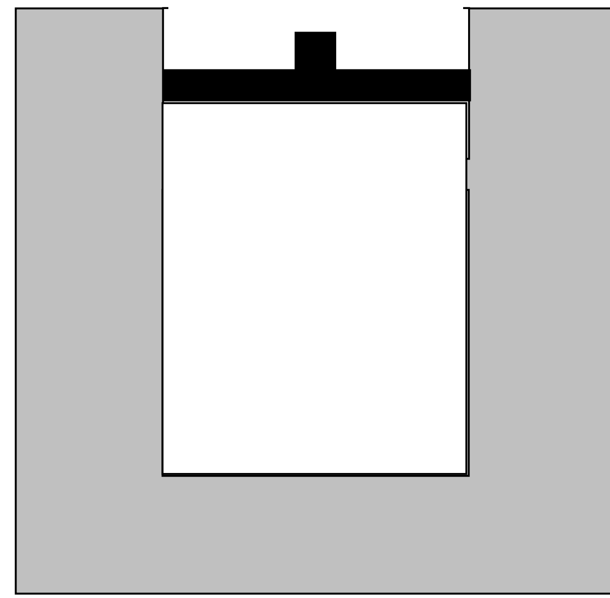
Question #1: During the process that occurs from time *A* to time *B*, which of the following is true: (a) positive work is done *on* the gas *by* the environment, **(b) positive work is done *by* the gas *on* the environment,** (c) no *net* work is done on or by the gas.

Step 1. We now begin Process #1: 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 when it is in the position shown in the diagram below:

Time *B*

Piston in new position.

Temperature of system has changed.



Question #2: During the process that occurs from time *A* to time *B*, the gas absorbs x joules of energy from the water. Which of the following is true: The total kinetic energy of all of the gas molecules (a) increases by more than x joules; (b) increases by x joules; (c) increases, but by less than x joules; (d) remains unchanged; (e) decreases by less than x joules; (f) decreases by x joules; (g) decreases by more than x joules.

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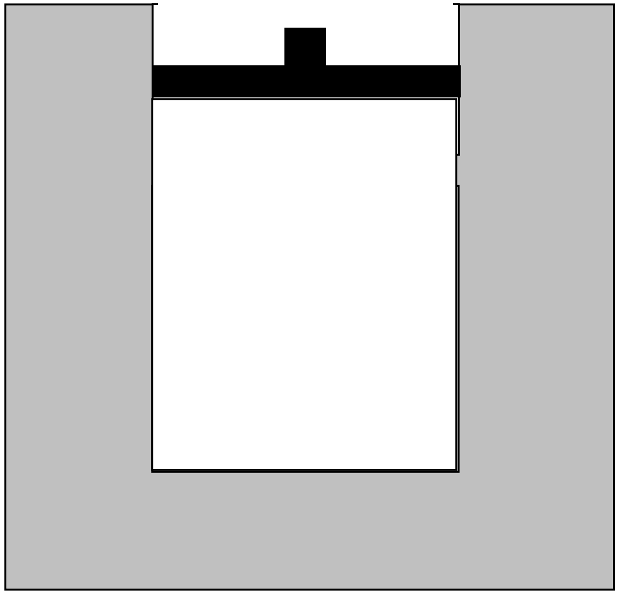
Temperature of system has changed.



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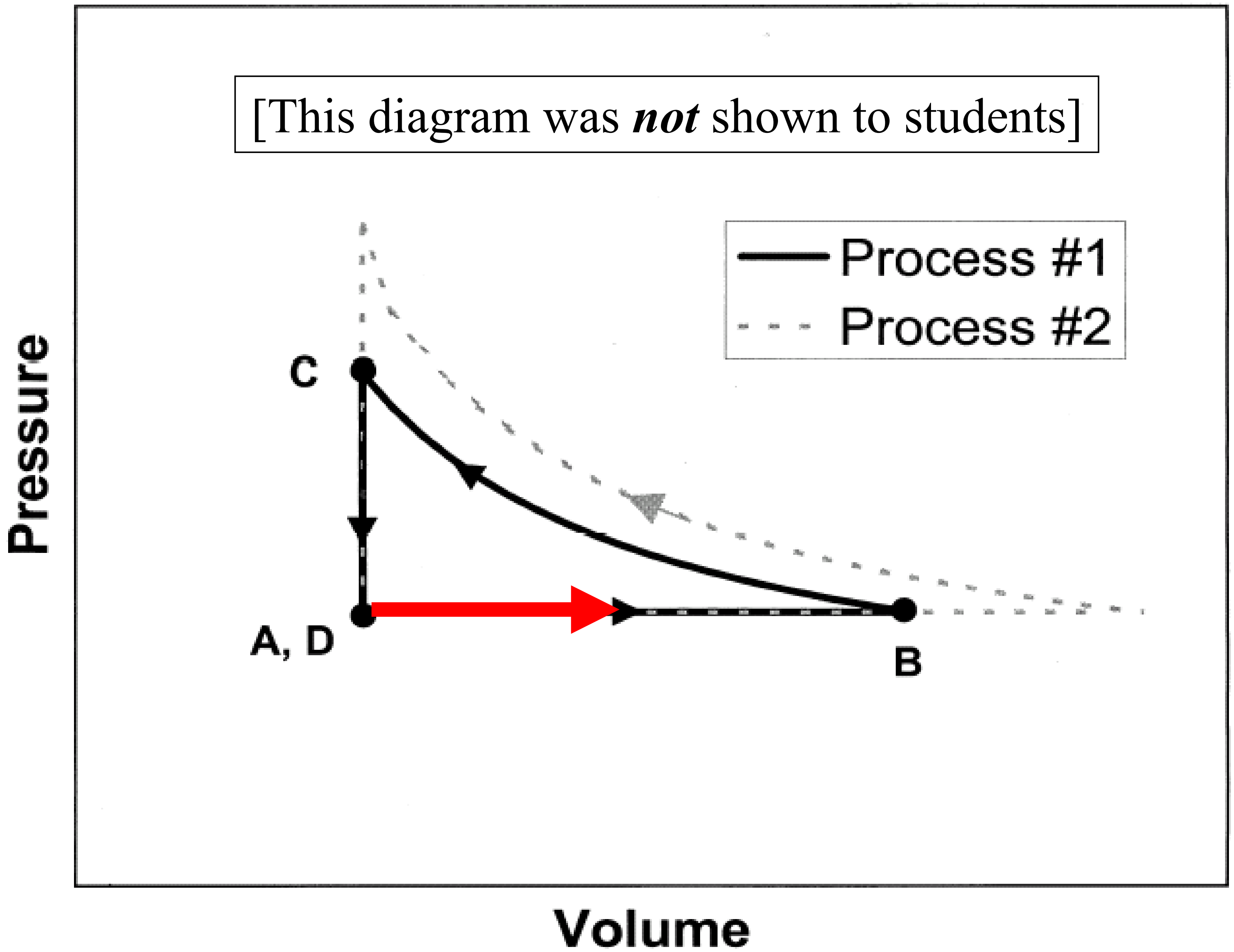
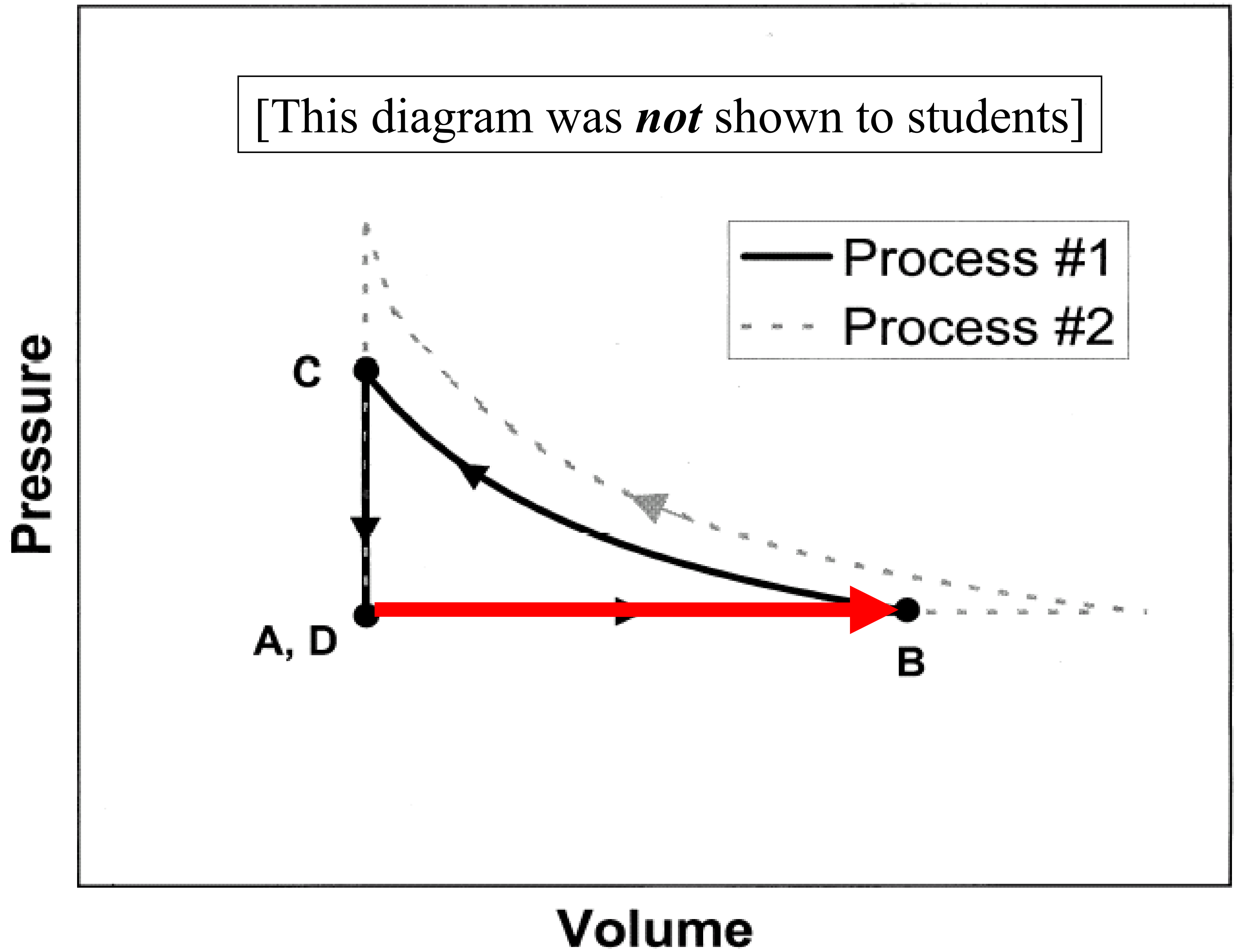

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



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

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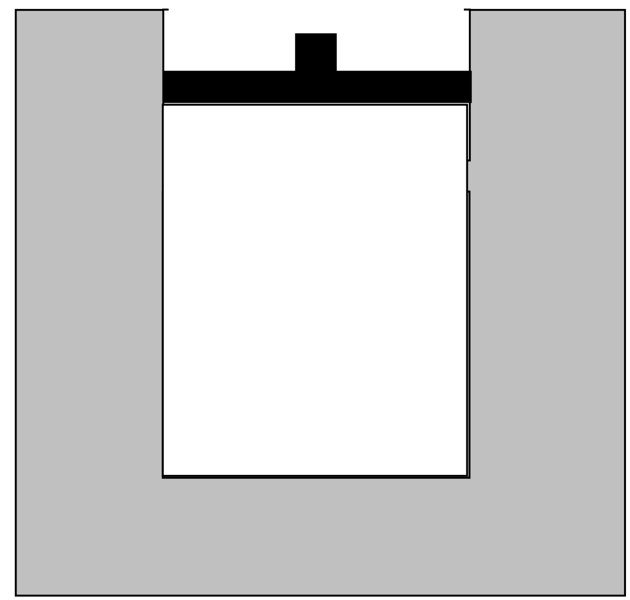
Piston in new position.

Temperature of system has changed.



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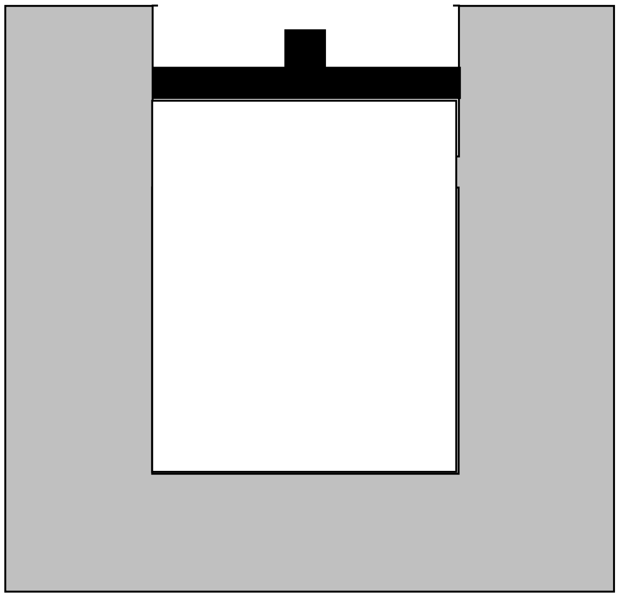

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Example of Correct Student Explanation on Question #2

"*Some heat energy that comes in goes to expanding, and some goes to increasing the kinetic energy of the gas*."

Results on Question #2

(b) increases by *x* joules: **47%**

(c) increases, but by less than *x* joules: 41%

with correct explanation: 28%

with incorrect explanation: 13%

(d) remains unchanged: **9%**

uncertain: **3%**

Sample Student Explanations for "b" on Question #2 ("increases by *x* joules")

"*There would be conservation of energy. If you add that much, it's going to have to increase by that much.*"

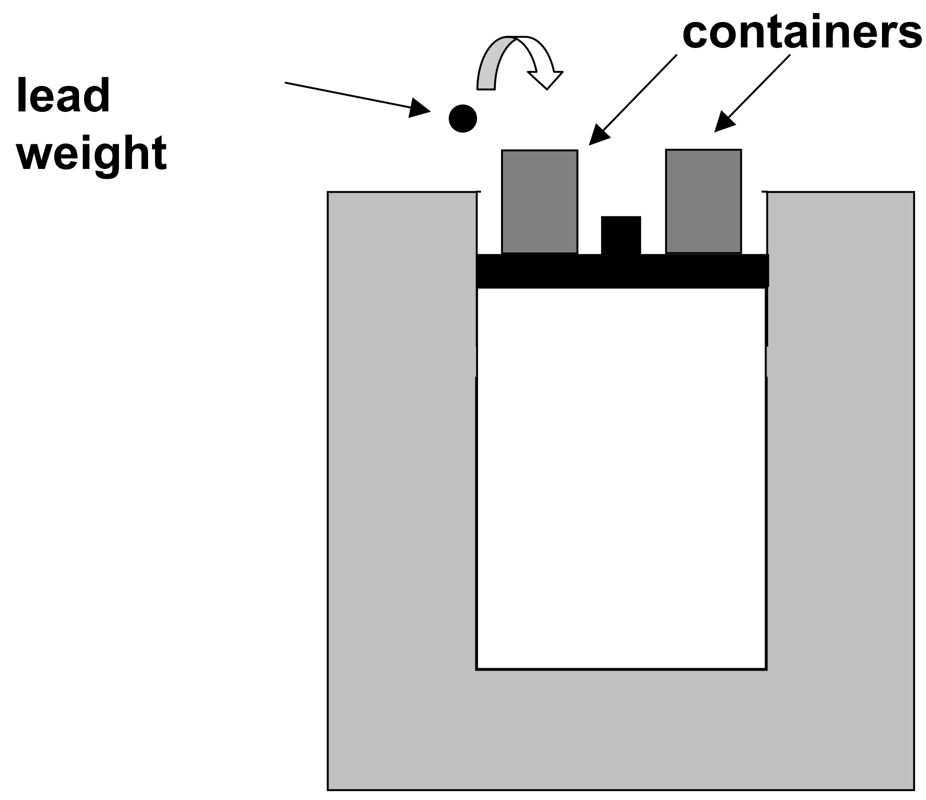
"*I assume there's no work done by expansion, that it doesn't take any kind of energy to expand the cylinder, which means that all of my energy is translated into temperature change.*"

Almost half of the students seem to be unaware that gas **loses** *energy as a result of expansion work.*

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. Failure to recognize "work" as a mechanism of energy transfer.
5. Confusion regarding isothermal processes and the thermal "reservoir."
6. Belief that net work done and net heat transferred during a cyclic process are zero.
7. Inability to apply the first law of thermodynamics.

Step 2. 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. While this happens, the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*. (That is, it remains at the temperature it reached at time *B,* after the water had been heated up.)



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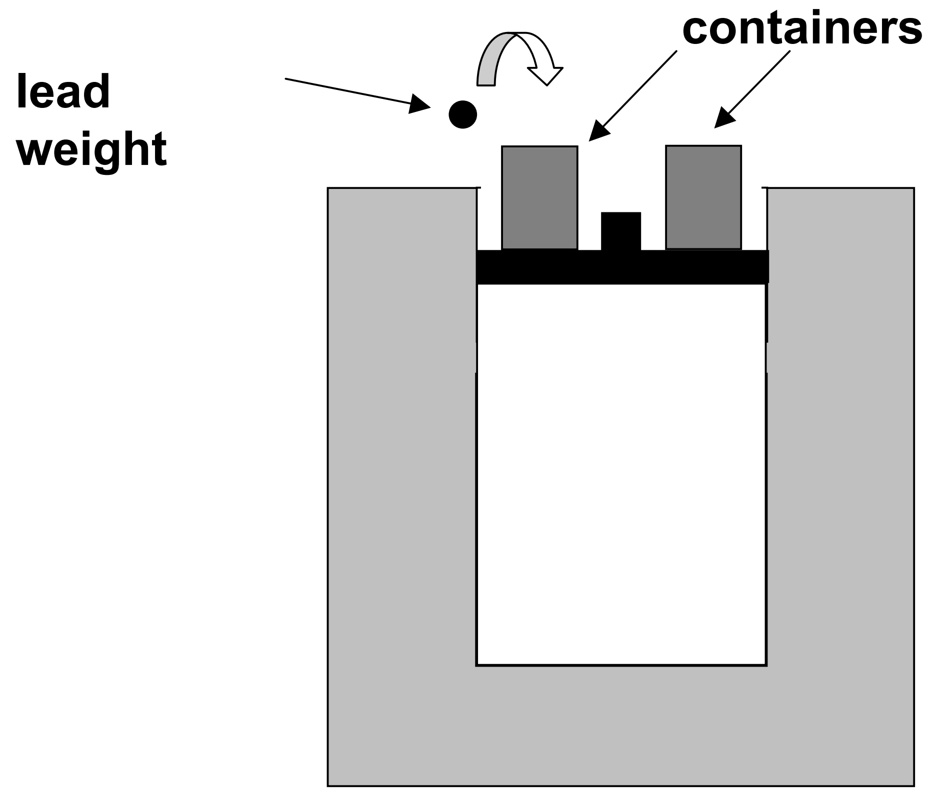

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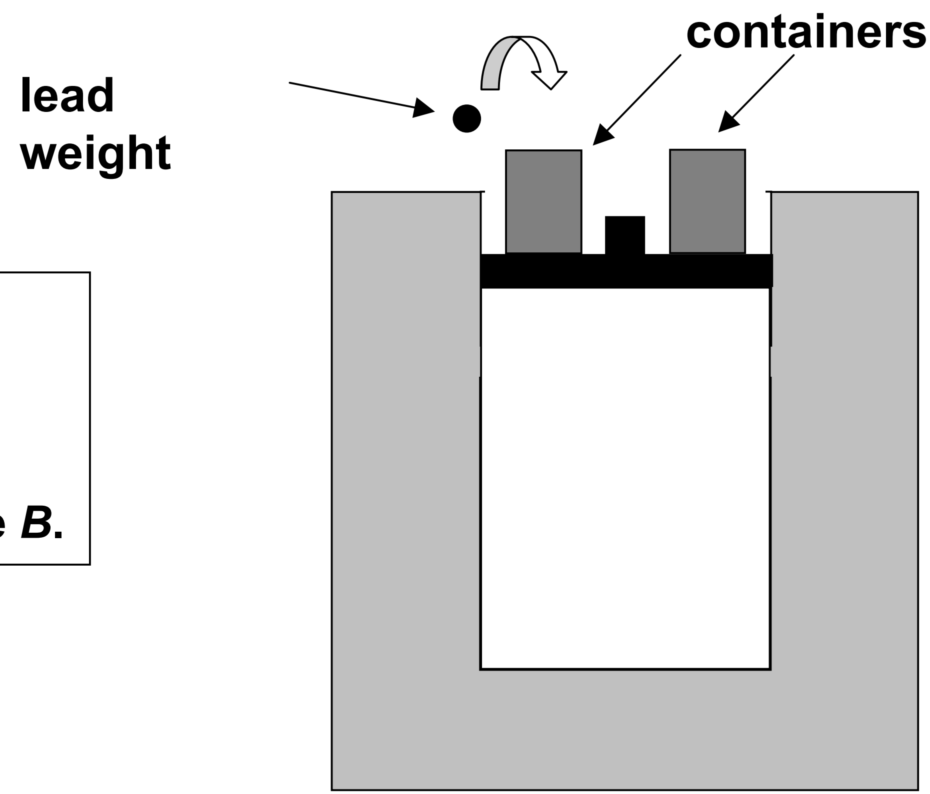
weights being added

Piston moves down slowly.

Temperature remains same as at time *B*.



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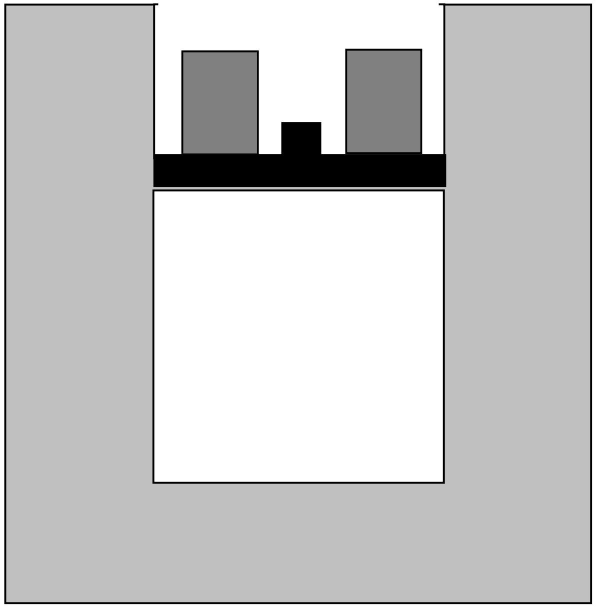
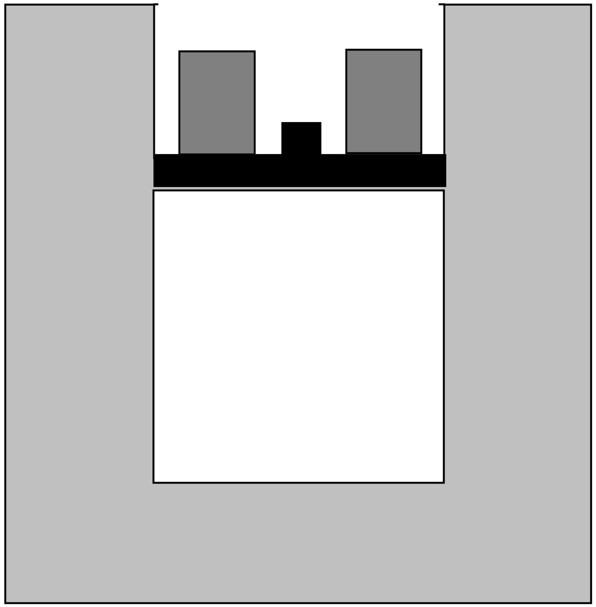


Step 3. At time *C* we stop adding lead weights to the container and the piston stops moving. (The weights that we have already added up until now are still in the containers.) The piston is now found to be at *exactly the same position it was at time **A*** .



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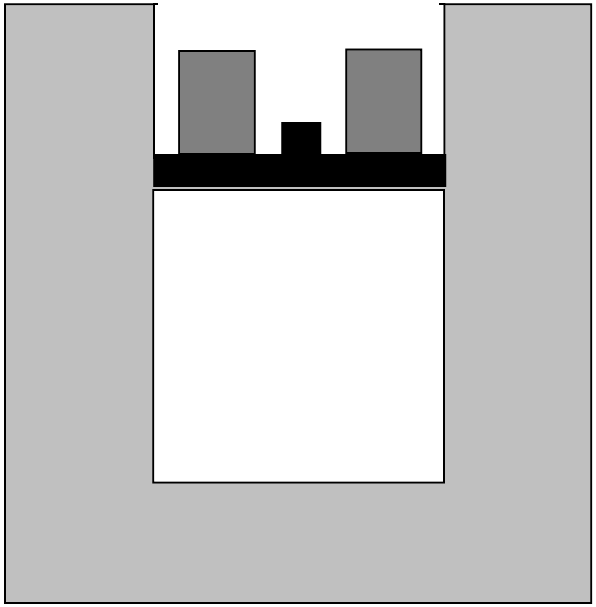
Time *C*

Weights in containers.

Piston in same position as at time *A*.

Temperature same as at time *B*.



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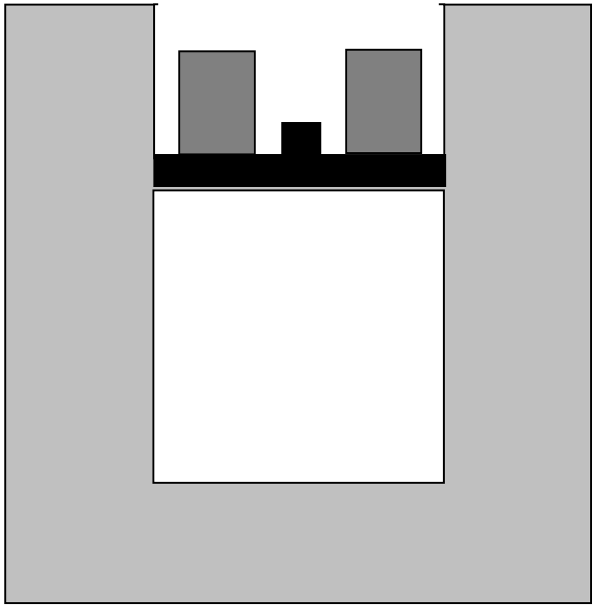

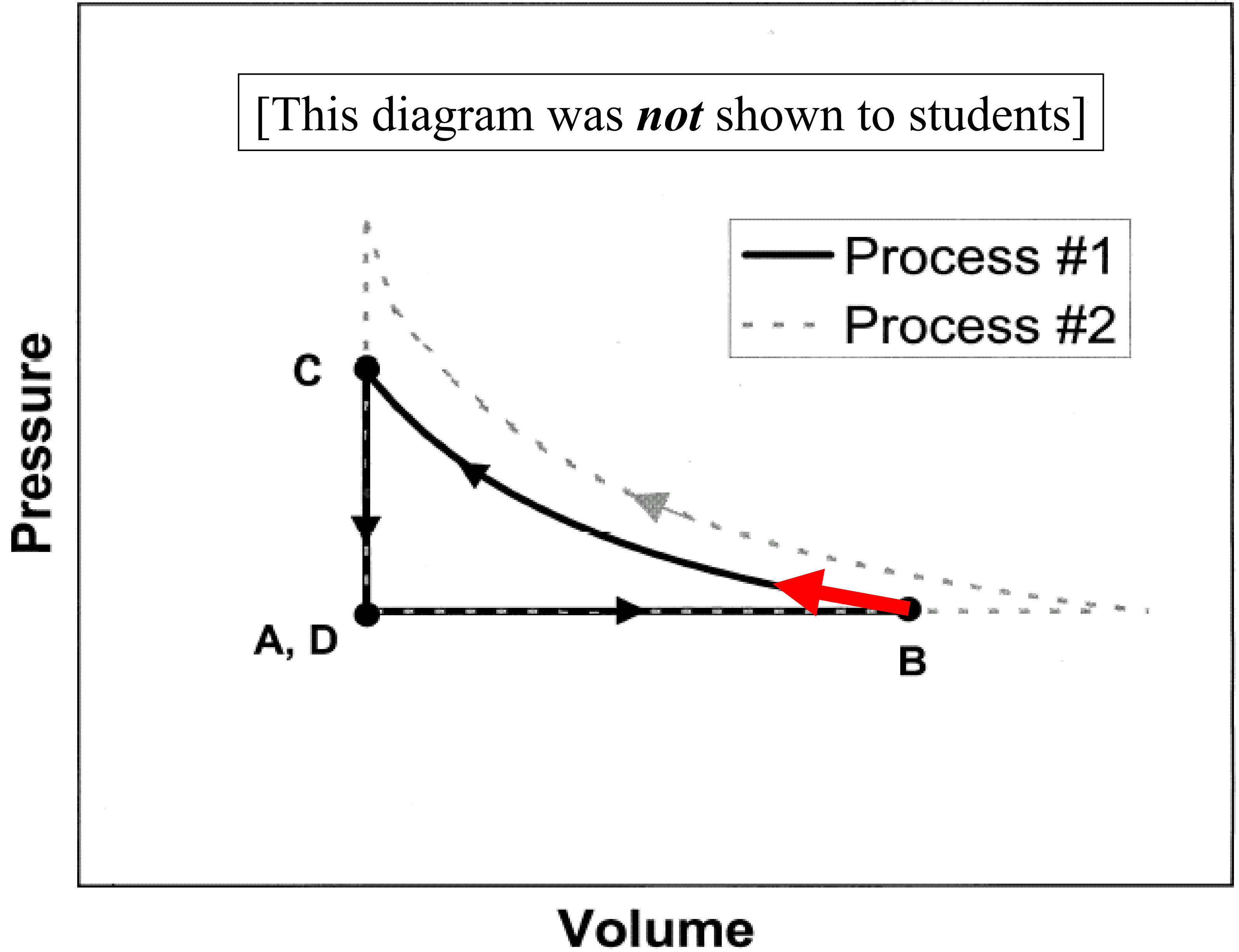
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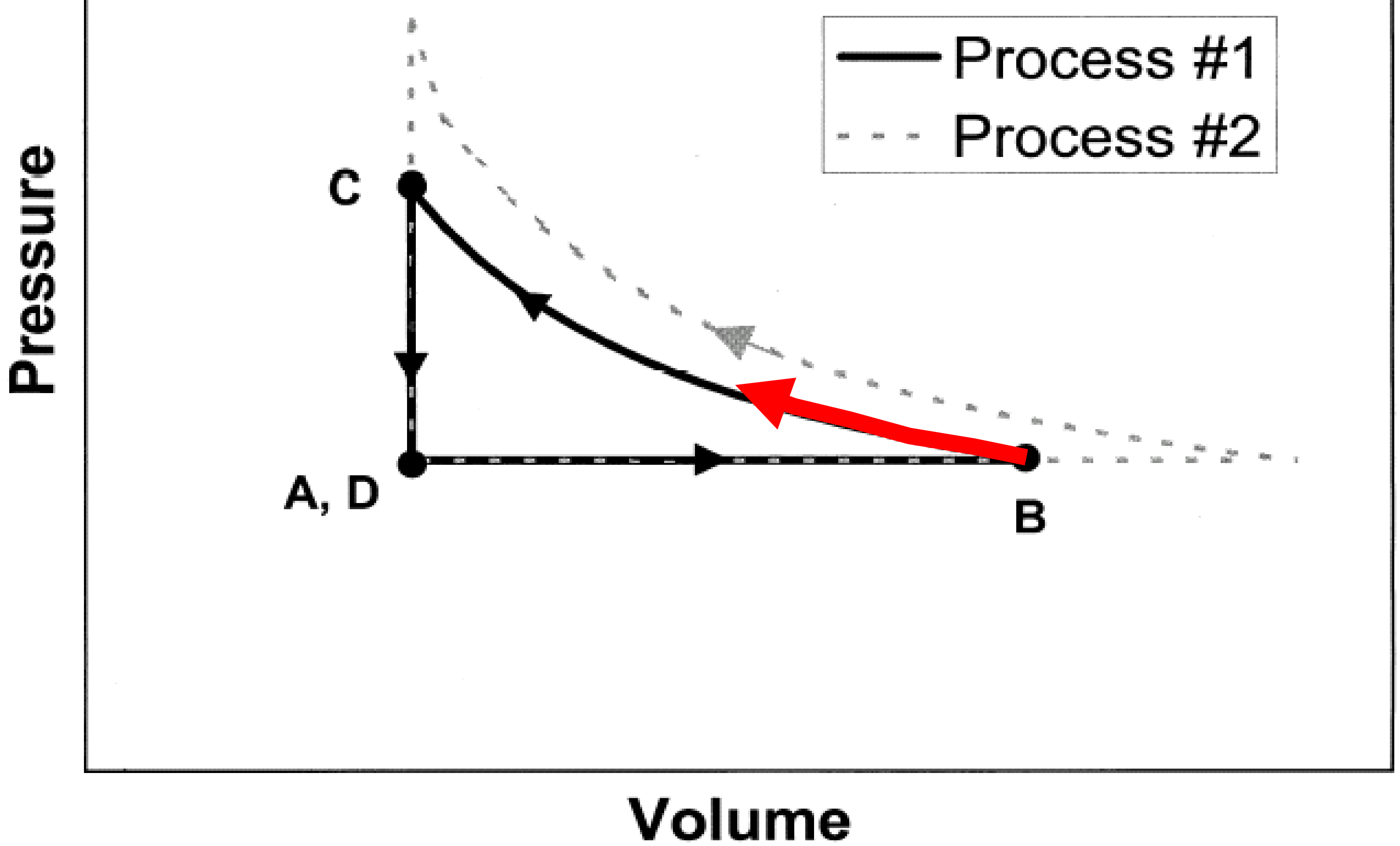
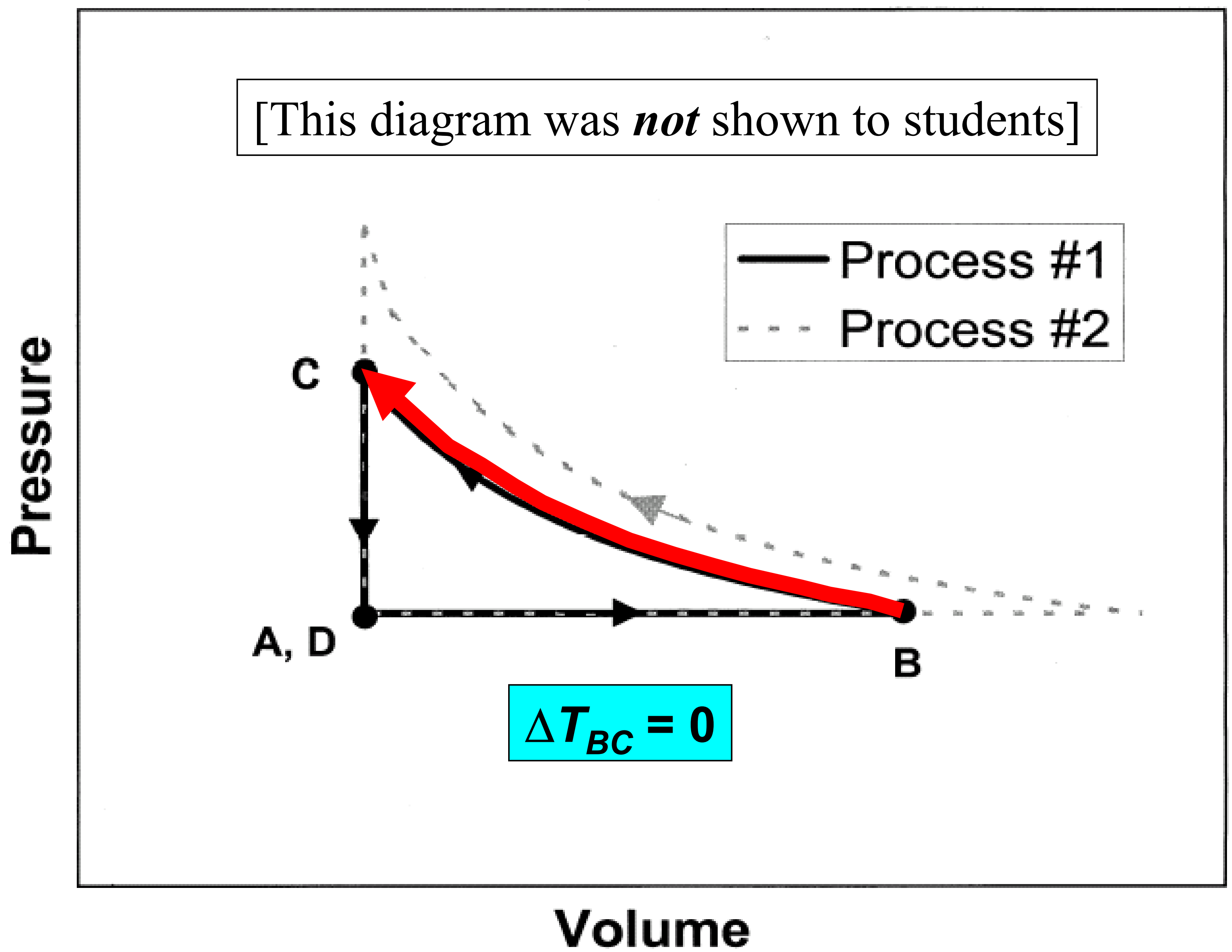
Process #1
Process #2
C
A, D
B
Pressure
Volume

[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

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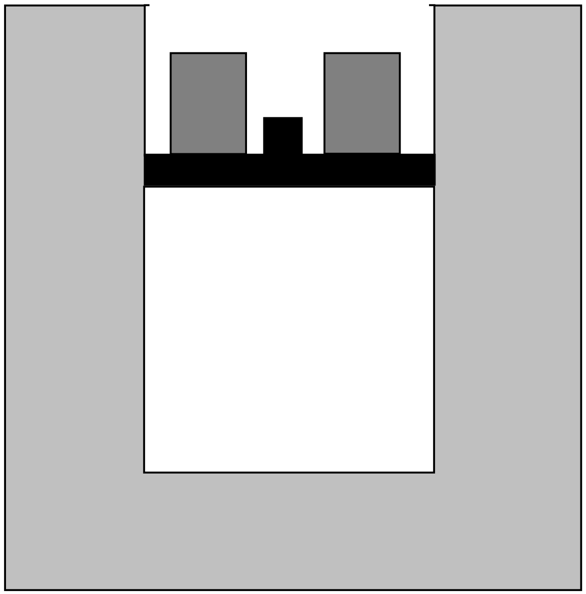
Time *C*

Weights in containers.

Piston in same position as at time *A*.

Temperature same as at time *B*.



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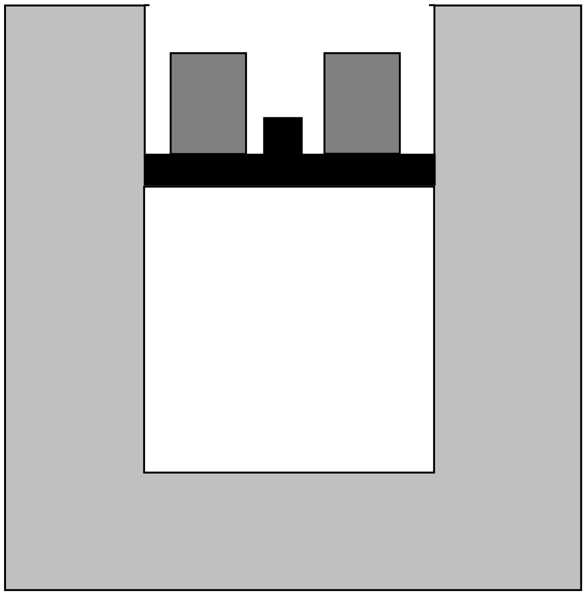
Time *C*

Weights in containers.

Piston in same position as at time *A*.

Temperature same as at time *B*.



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?

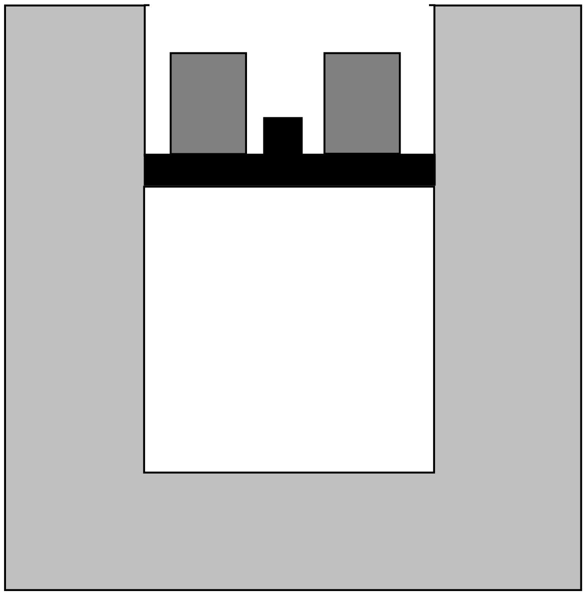
Step 3. At time *C* we stop adding lead weights to the container and the piston stops moving. (The weights that we have already added up until now are still in the containers.) The piston is now found to be at *exactly the same position it was at time* ***A*** .

Time *C*

Weights in containers.

Piston in same position as at time *A*.

Temperature same as at time *B*.



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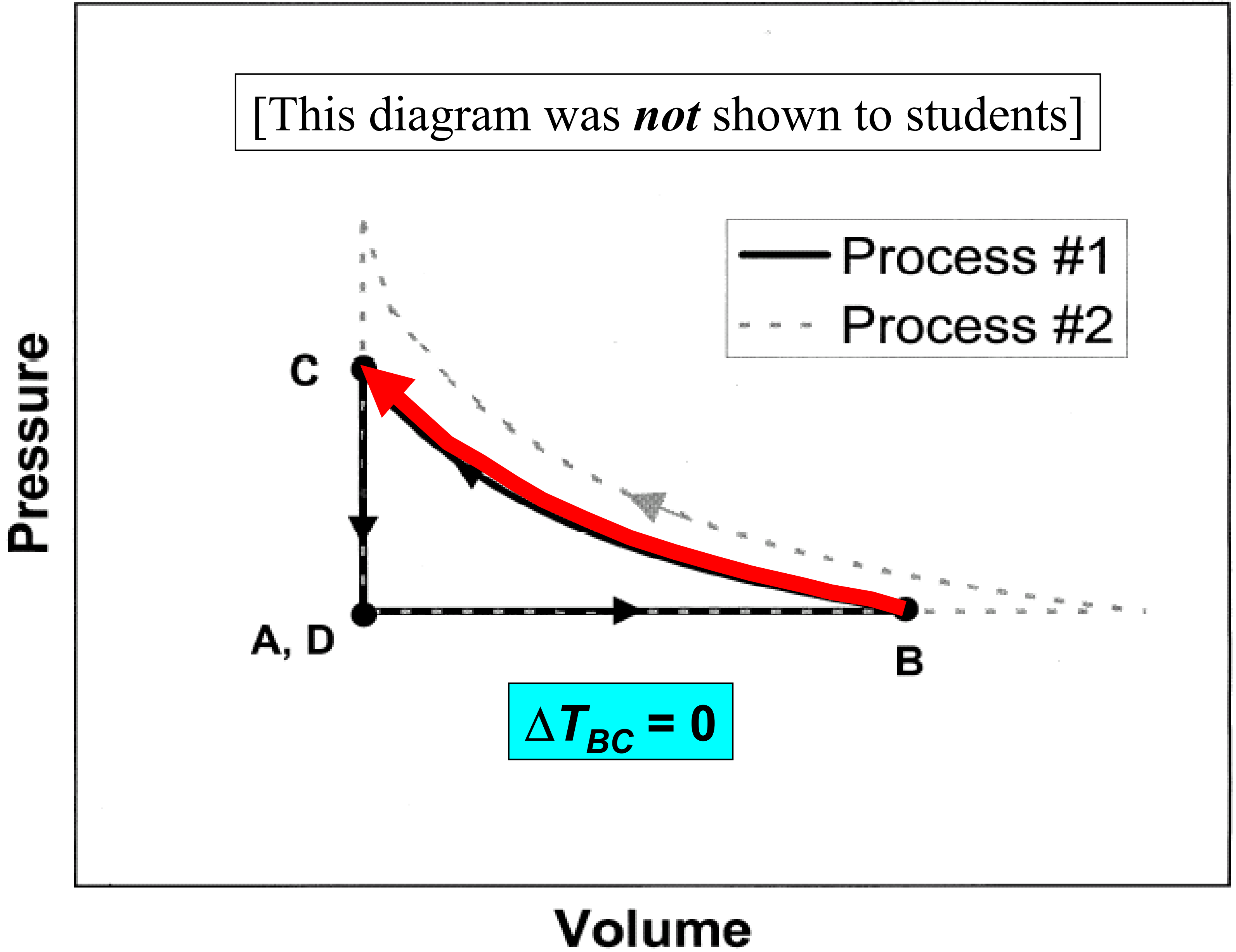
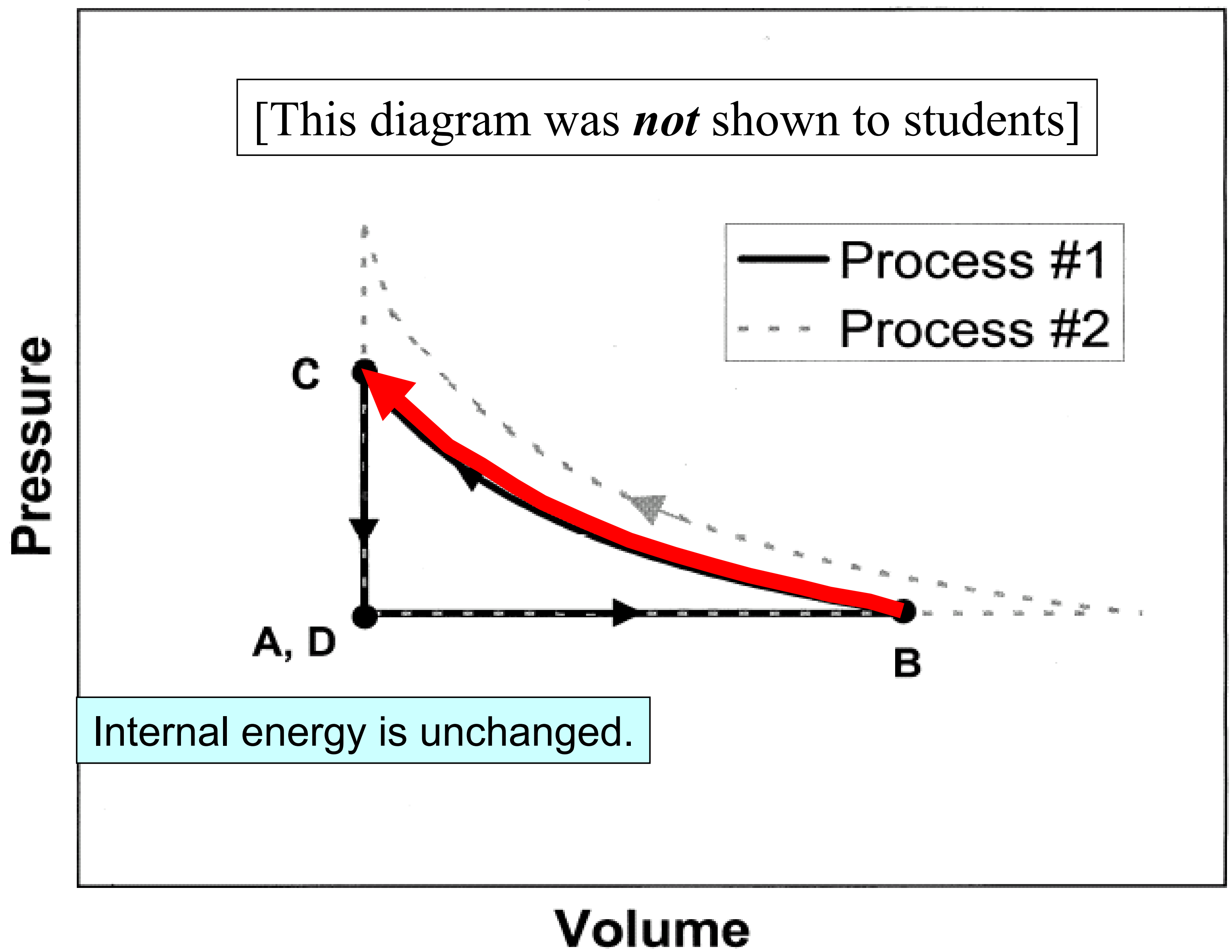
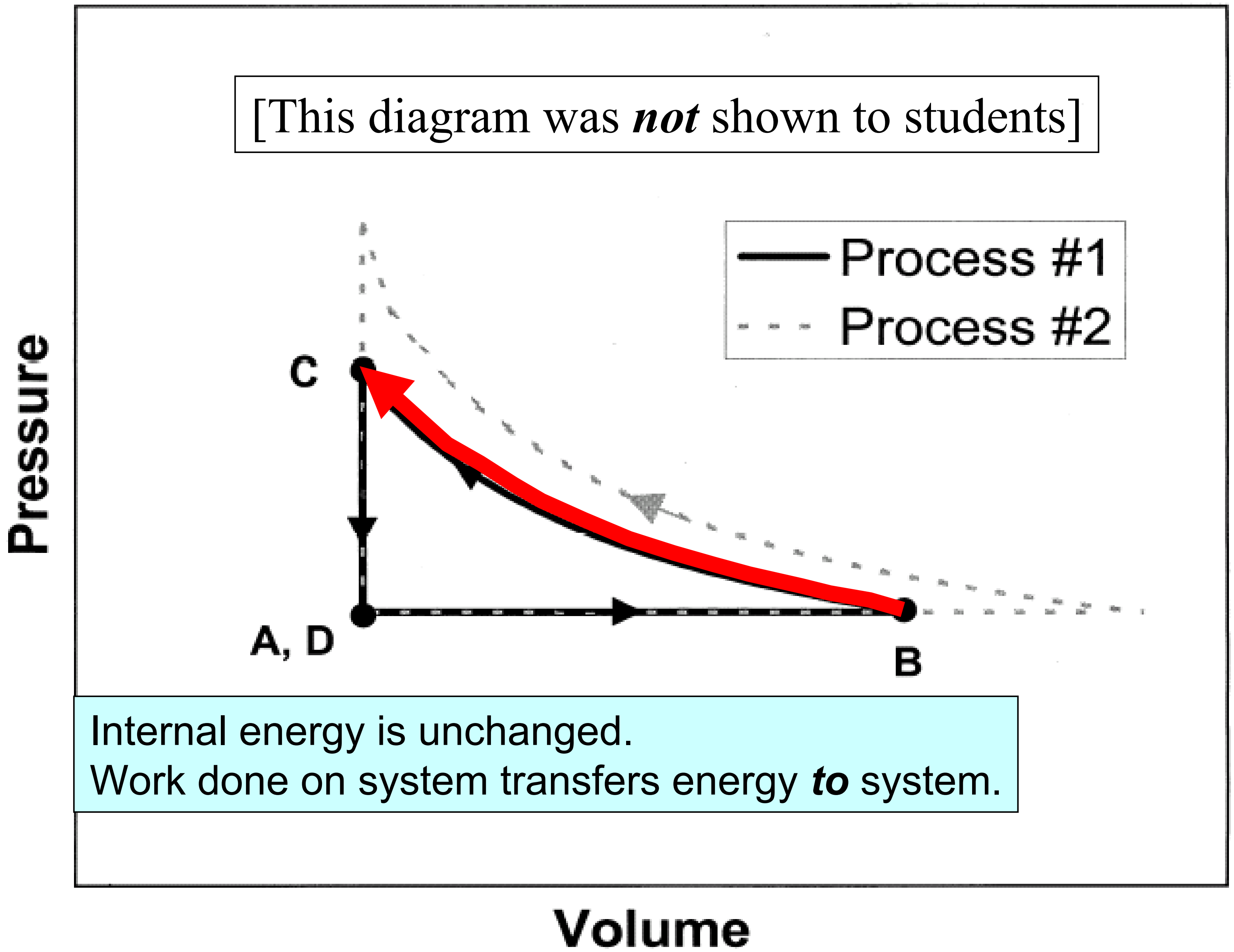
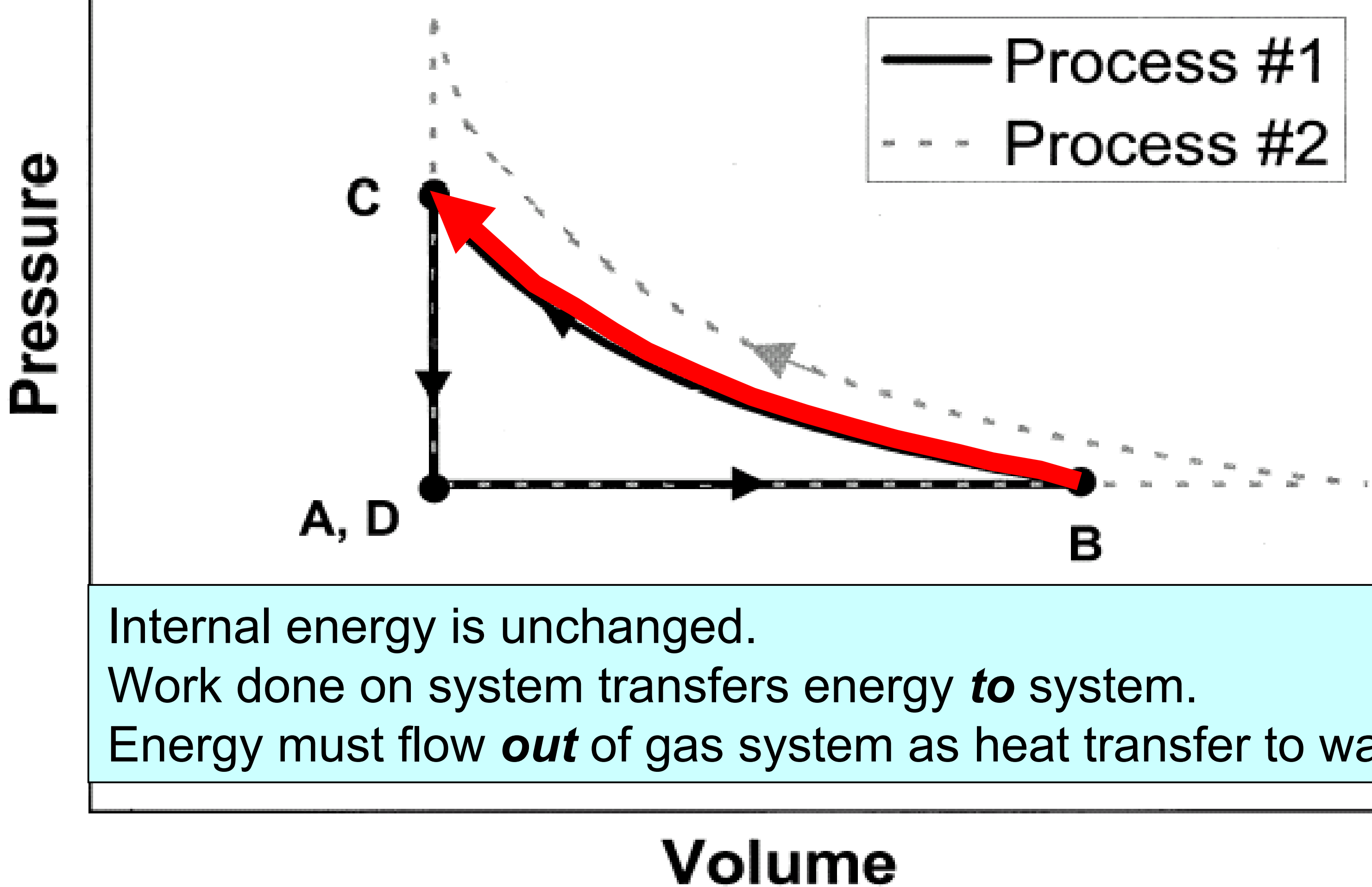

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
$\Delta T_{BC} = 0$
Pressure
Volume


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

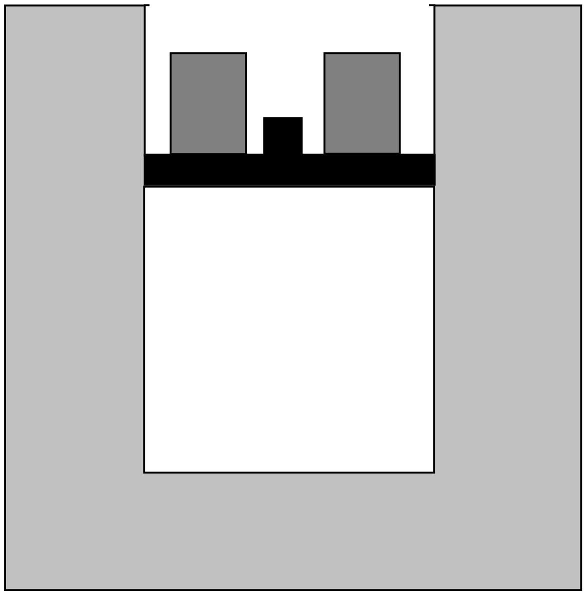
Step 3. At time *C* we stop adding lead weights to the container and the piston stops moving. (The weights that we have already added up until now are still in the containers.) The piston is now found to be at *exactly the same position it was at time **A*** .

Time *C*

Weights in containers.

Piston in same position as at time *A*.

Temperature same as at time *B*.



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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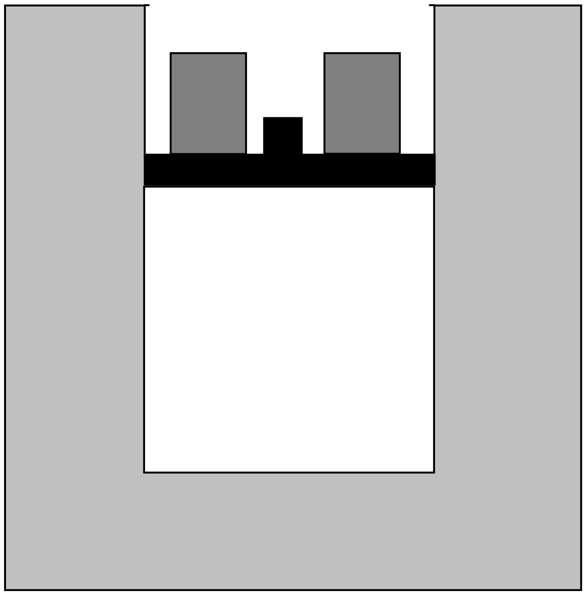
Time *C*

Weights in containers.

Piston in same position as at time *A*.

Temperature same as at time *B*.



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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*."

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

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. Failure to recognize "work" as a mechanism of energy transfer.
5. Confusion regarding isothermal processes and the thermal "reservoir."
6. Belief that net work done and net heat transferred during a cyclic process are zero.
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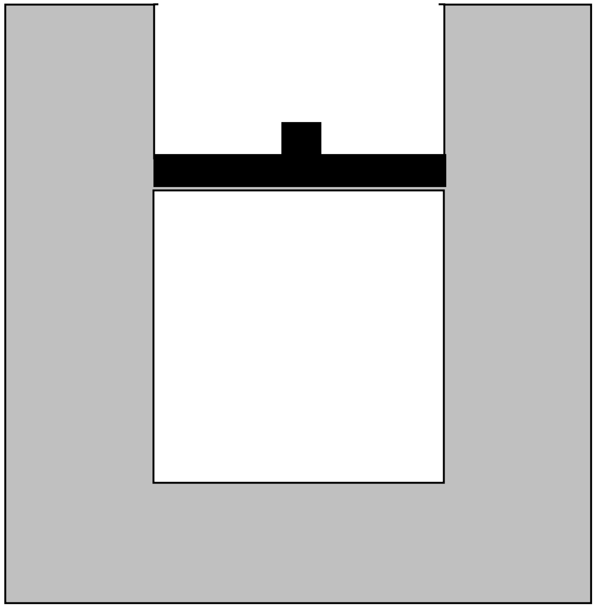
Step 4. Now, the piston is locked into place so it *cannot move*; the weights are removed from the piston. The system is left to sit in the room for many hours, and eventually the entire system cools back down to the same room temperature it had at time *A*. When this finally happens, it is time *D*.



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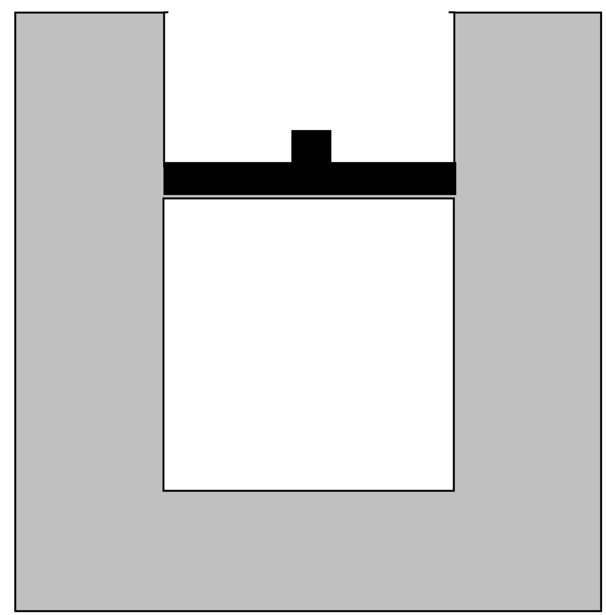

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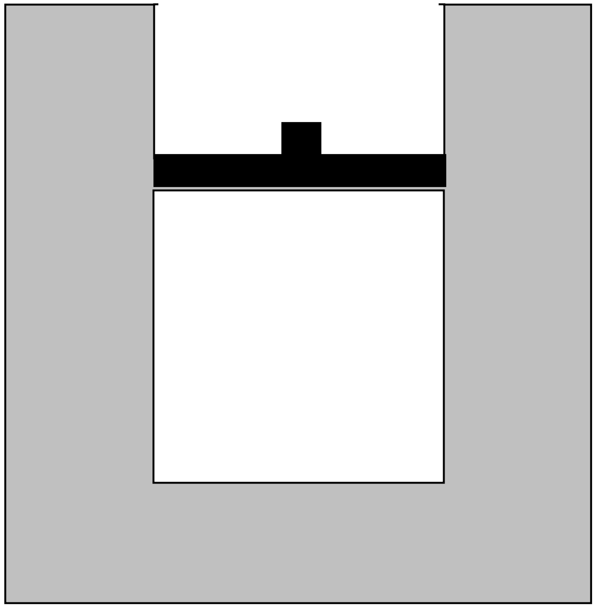
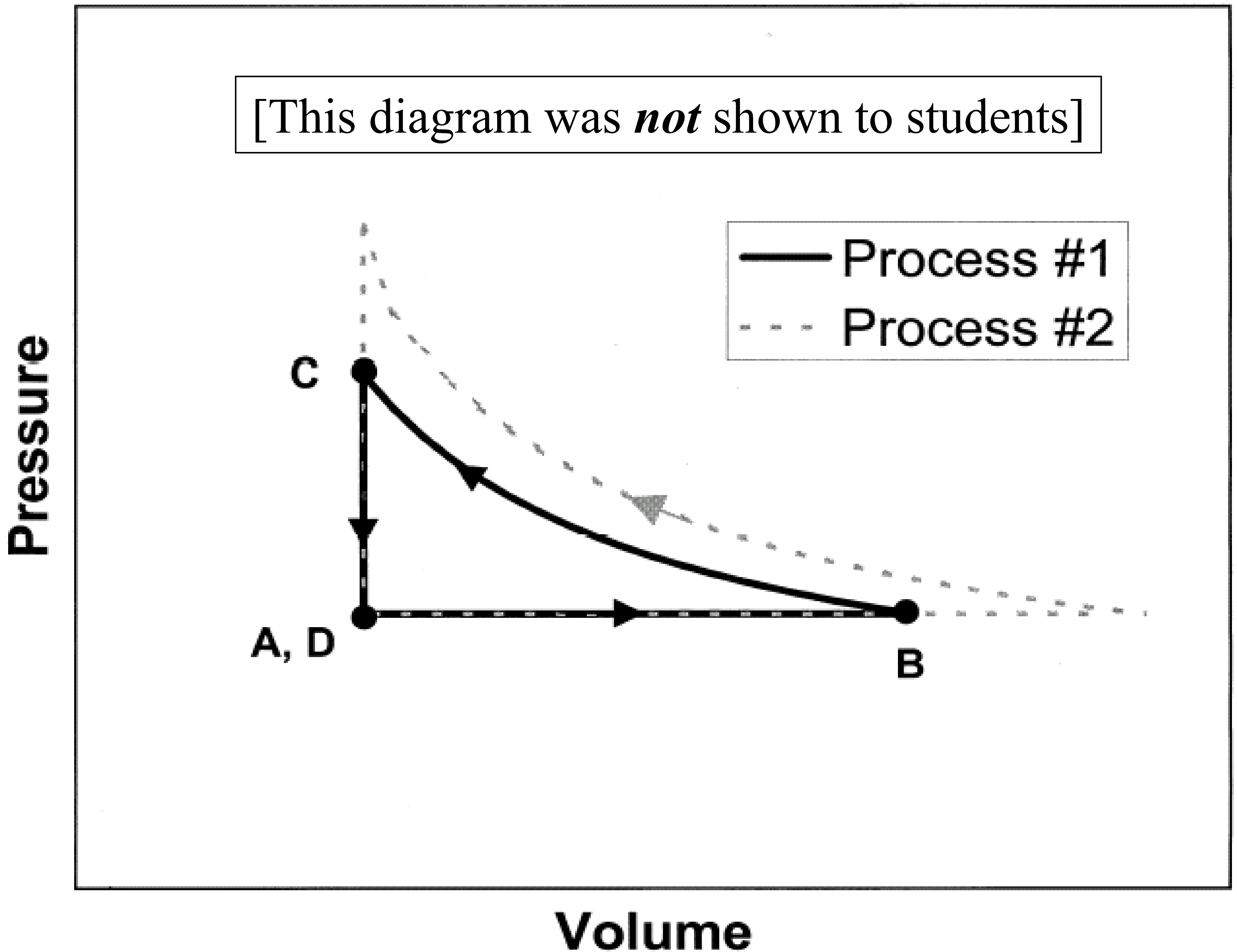
Time *D*

Piston in same position as at time *A*.

Temperature same as at time *A*.

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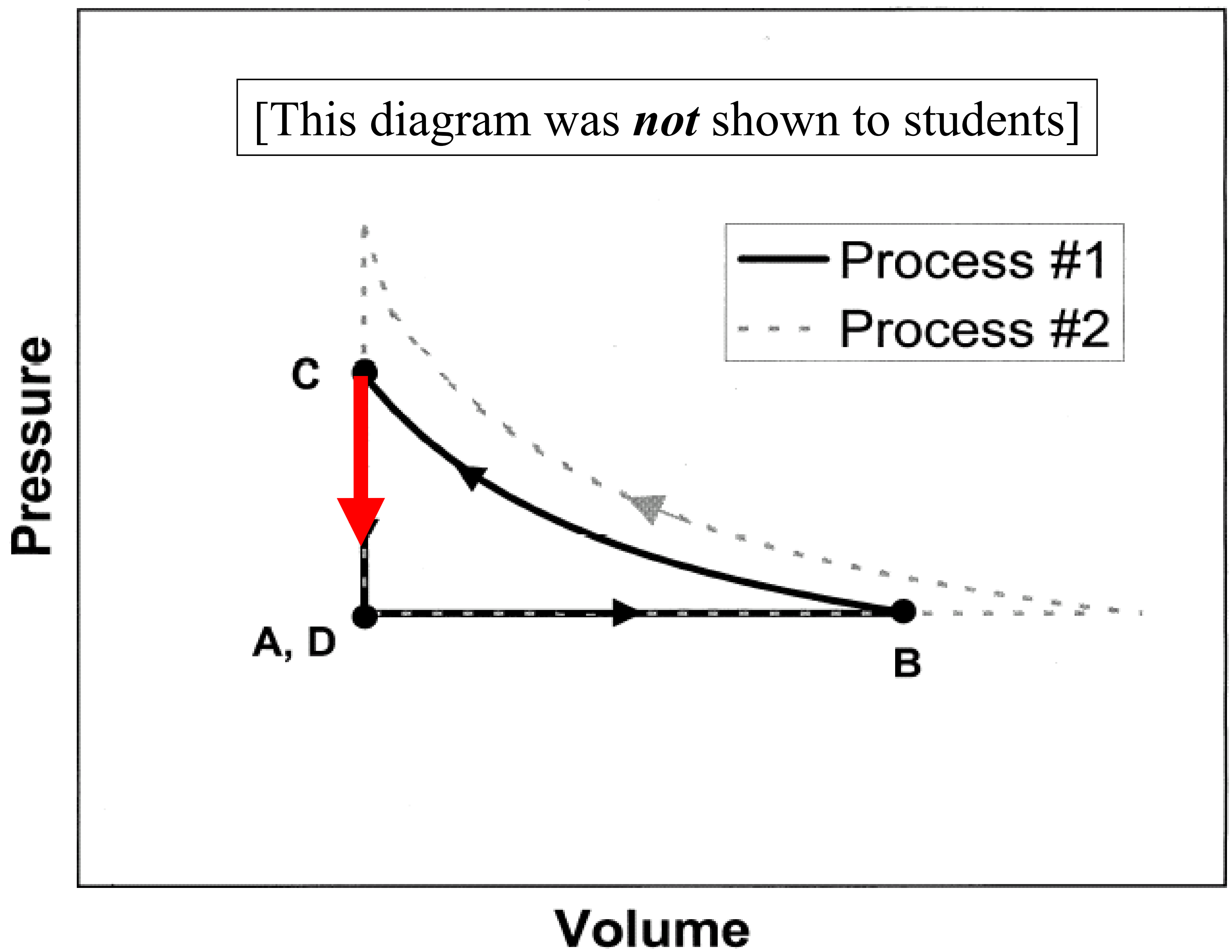
Process #1
Process #2
C
A, D
B
Pressure
Volume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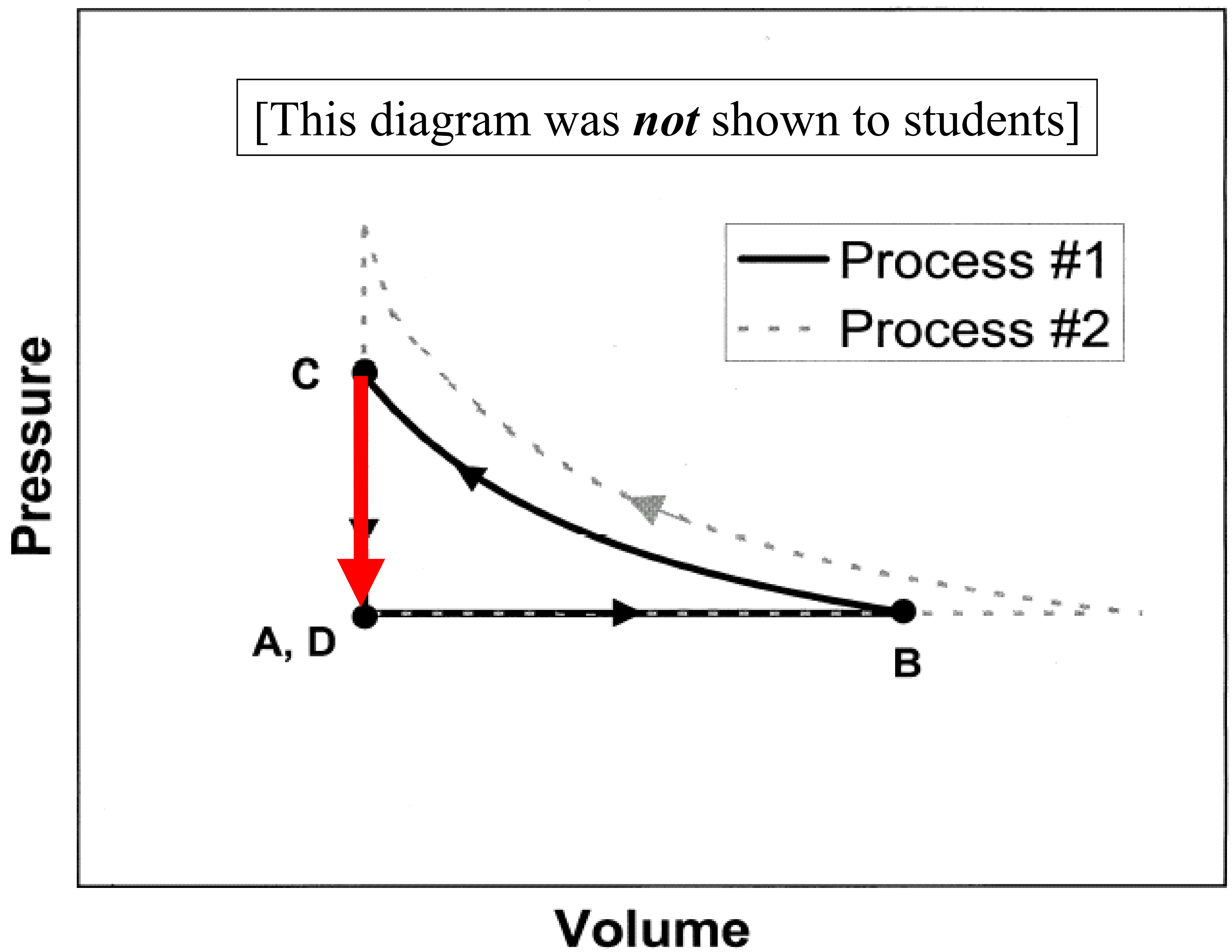
Process #1
Process #2
C
A, D
B
Pressure
Volume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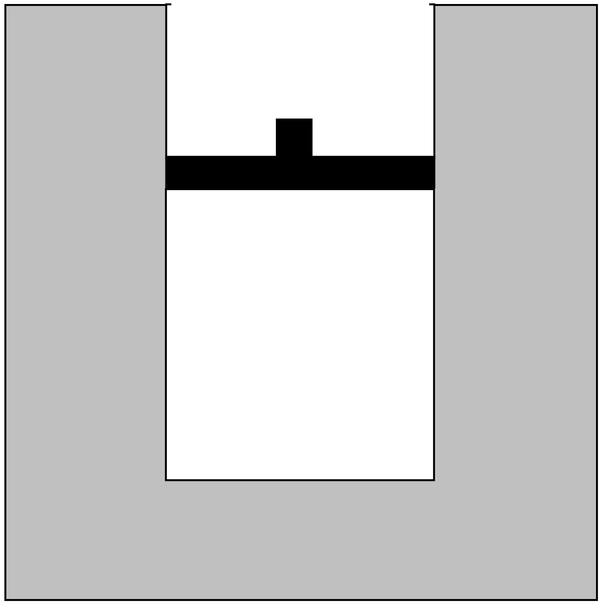
Process #1
Process #2
C
A, D
B
Pressure
Volume



Time *D*

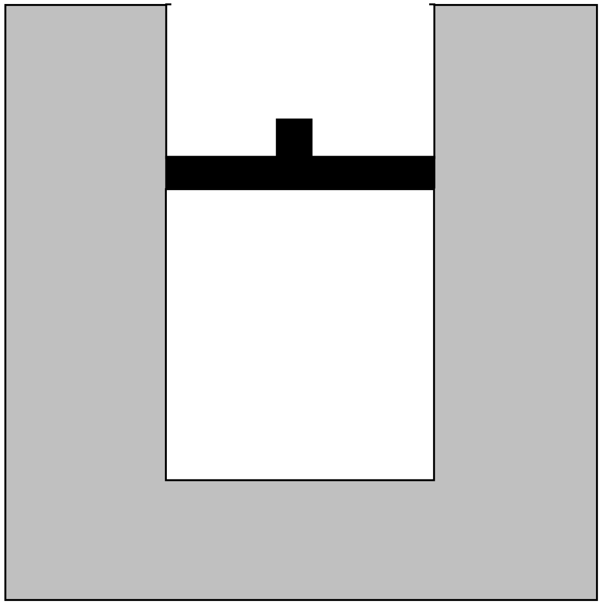
Piston in same position as at time *A*.

Temperature same as at time *A*.

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?



Time *D*

Piston in same position as at time *A*.

Temperature same as at time *A*.

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?

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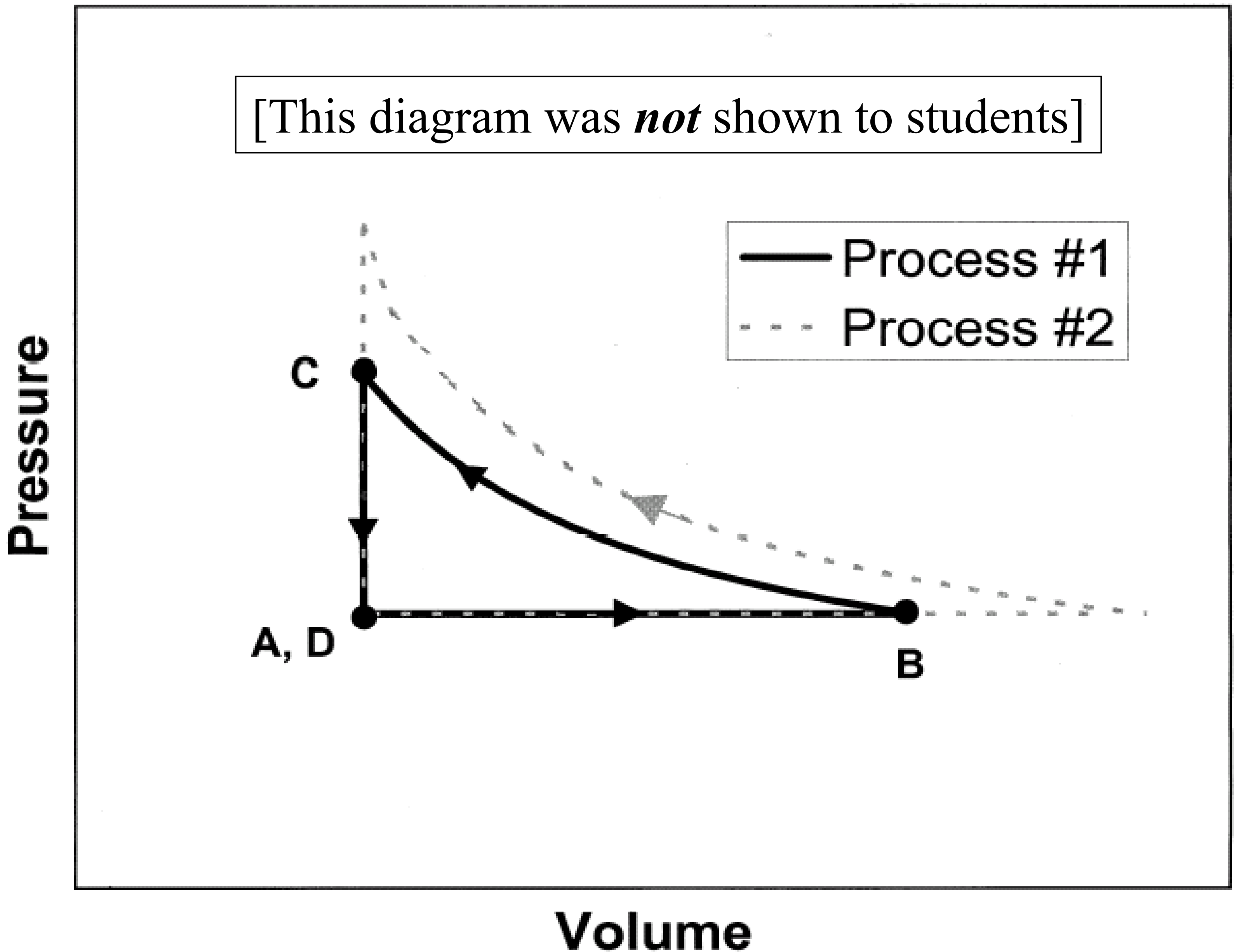
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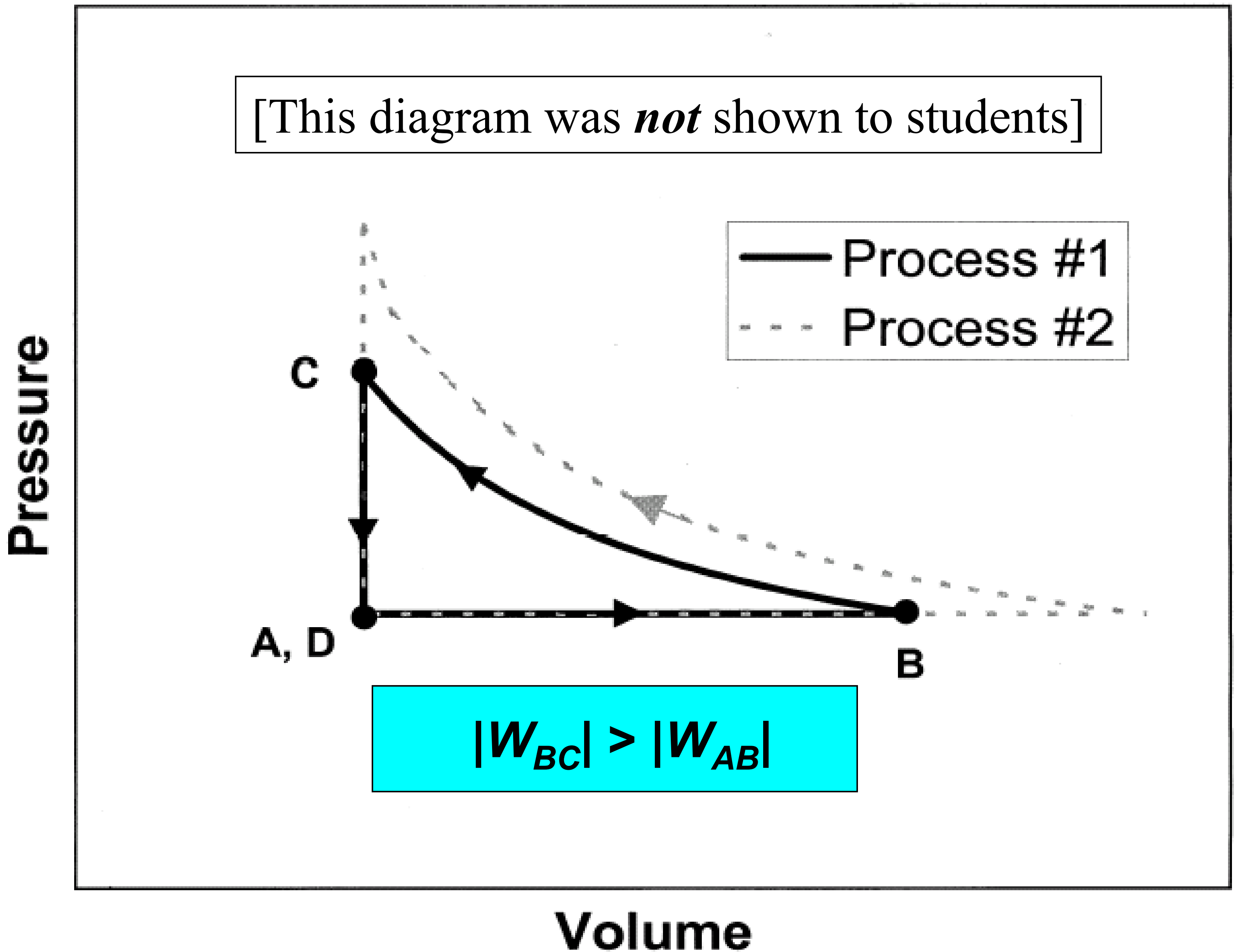
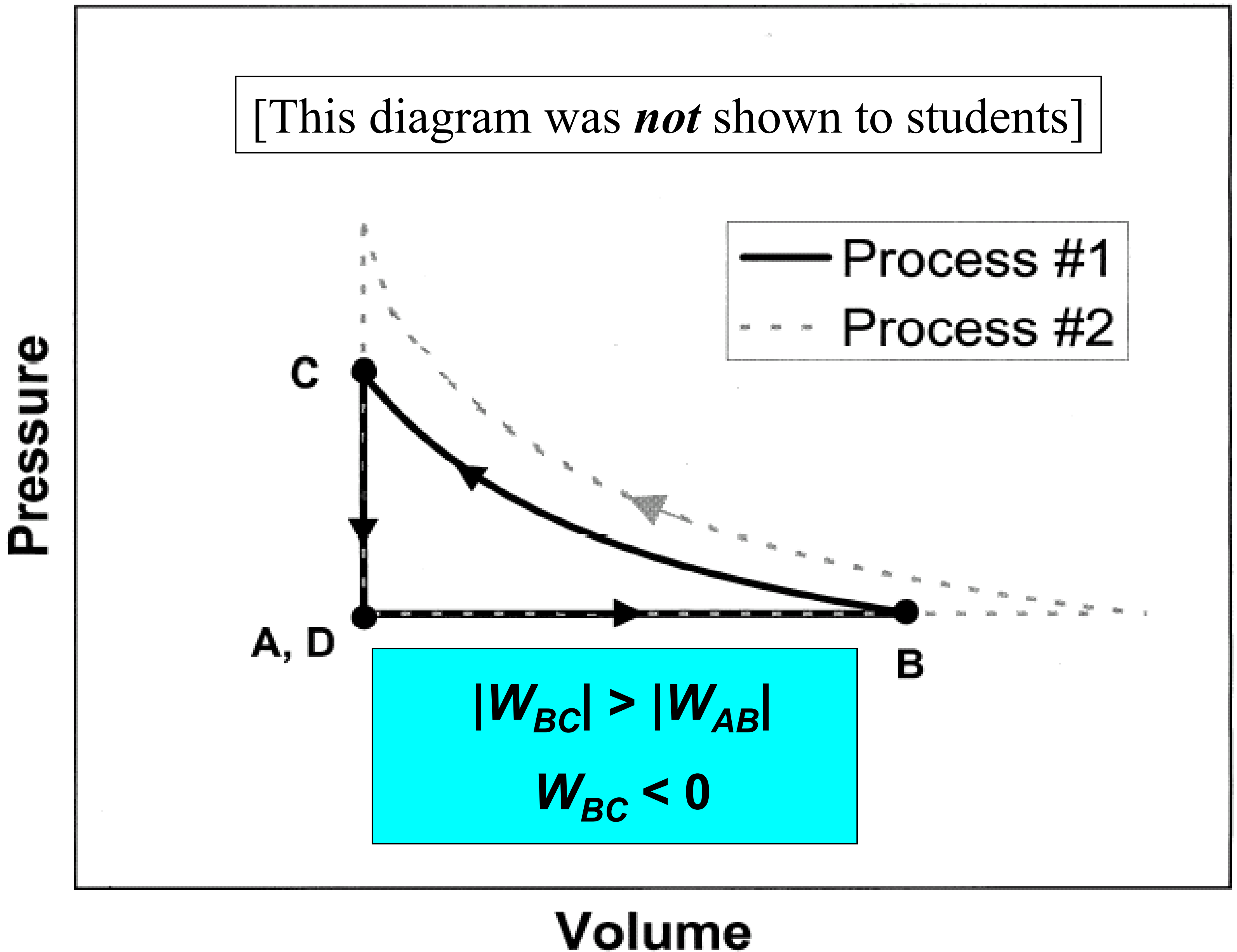
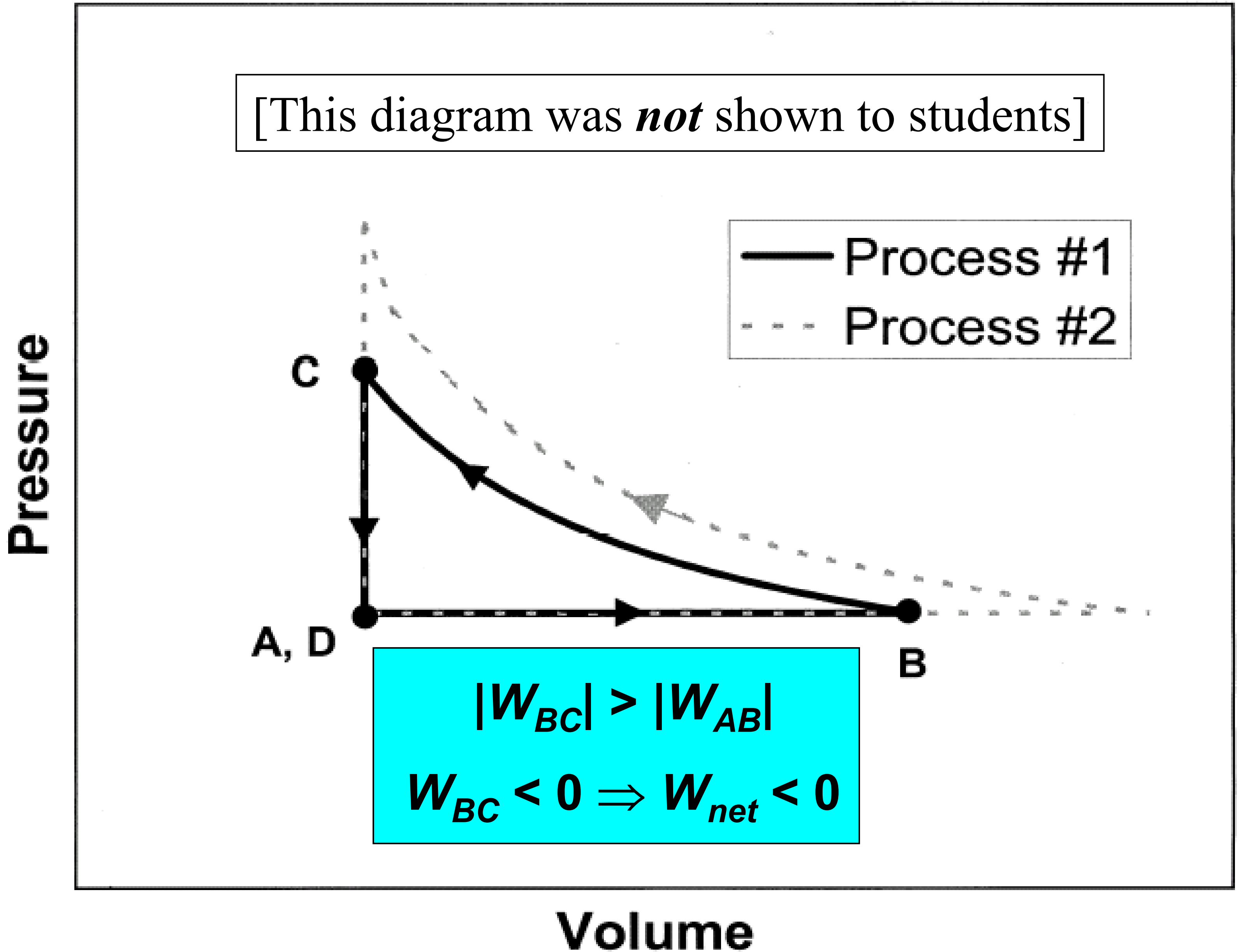
Process #1
Process #2
Pressure
C
A, D
B
Volume



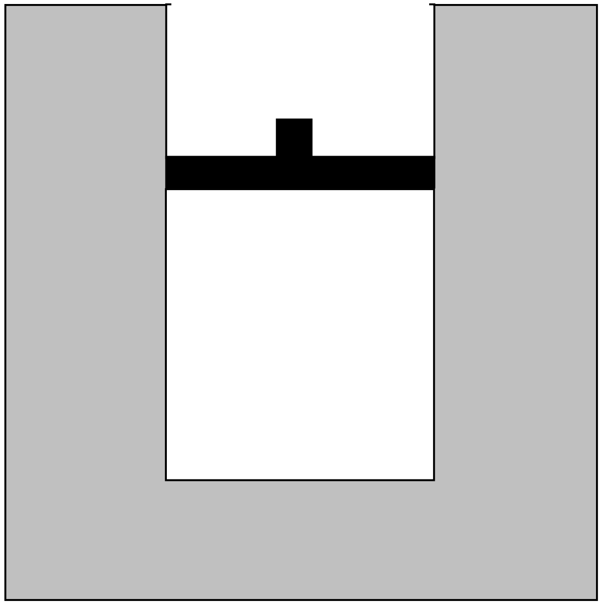
[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
$|W_{BC}| > |W_{AB}|$
Pressure
Volume



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



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



Time *D*

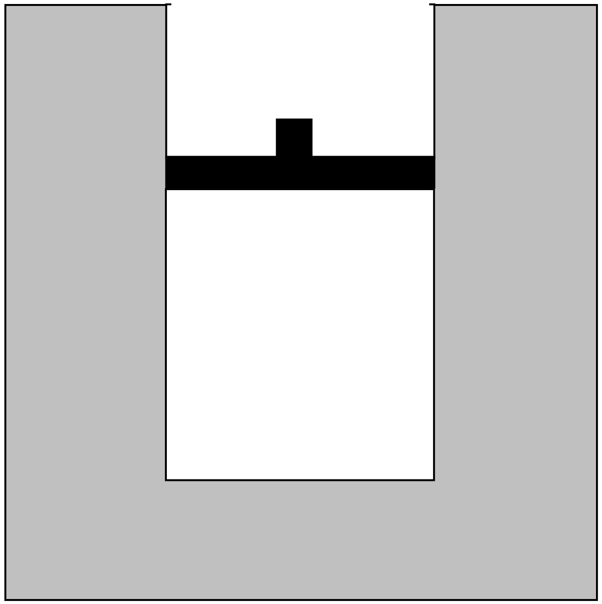
Piston in same position as at time *A*.

Temperature same as at time *A*.

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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Piston in same position as at time *A*.

Temperature same as at time *A*.

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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]***

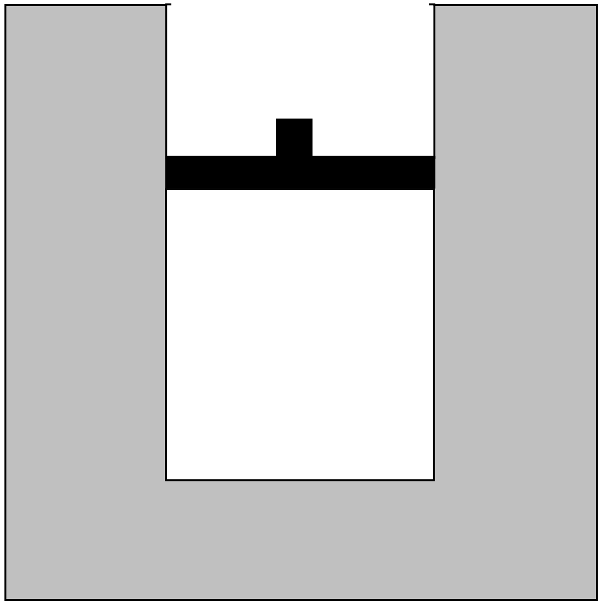
No response: 3%

Even after being asked to draw a *P-V* diagram for Process #1, 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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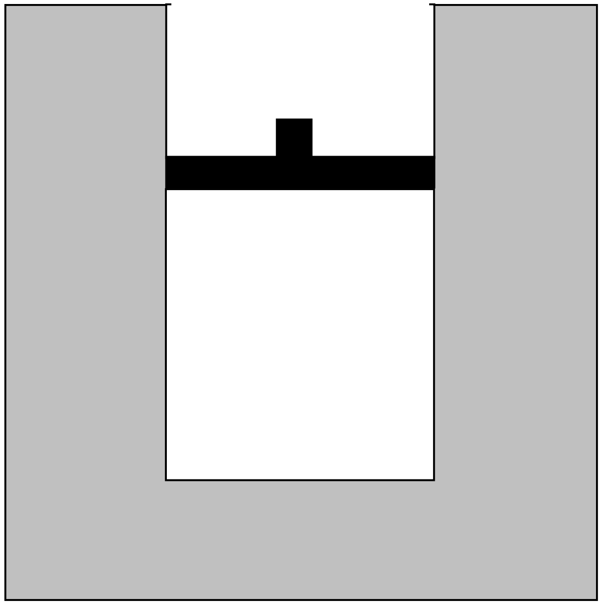

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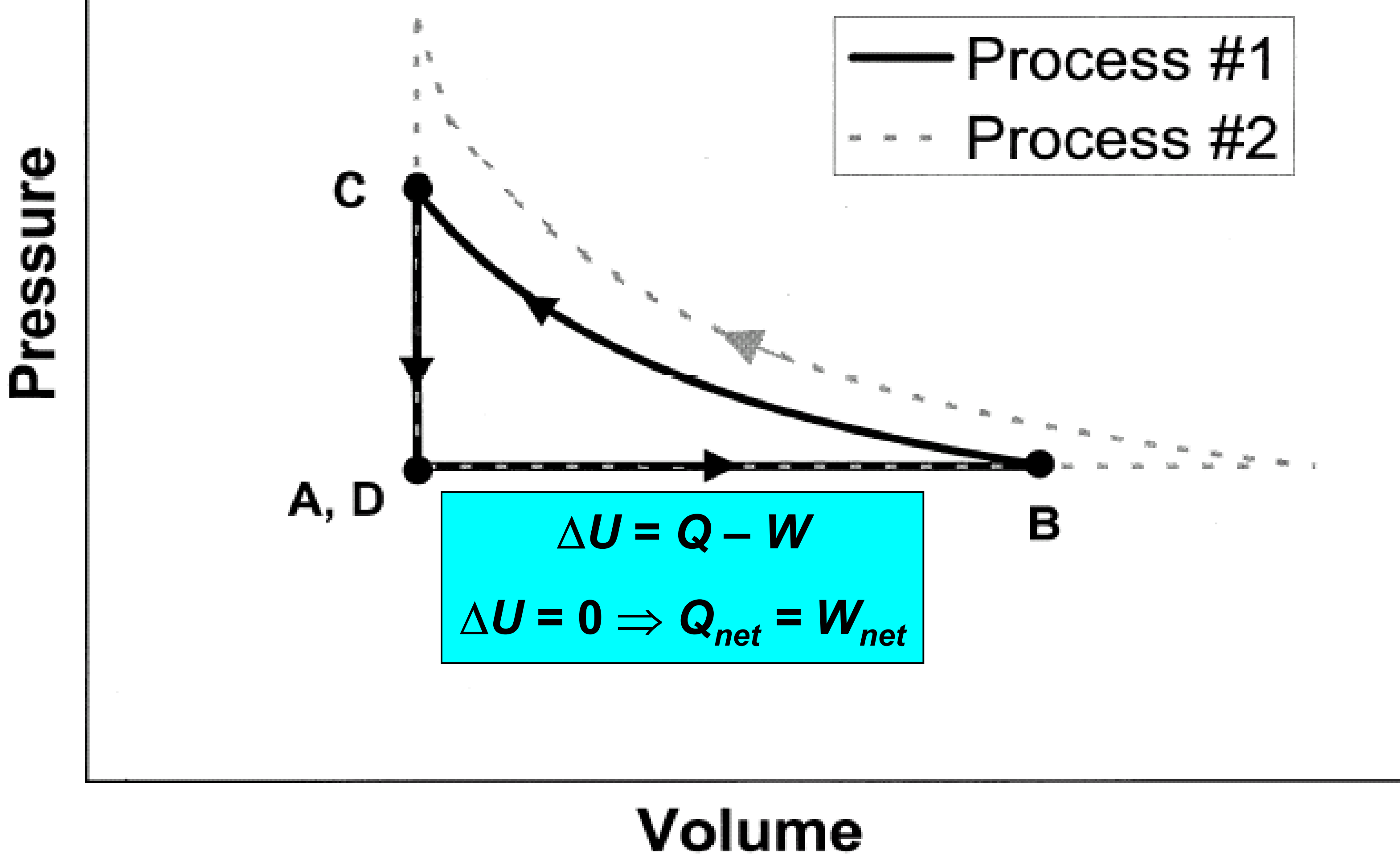
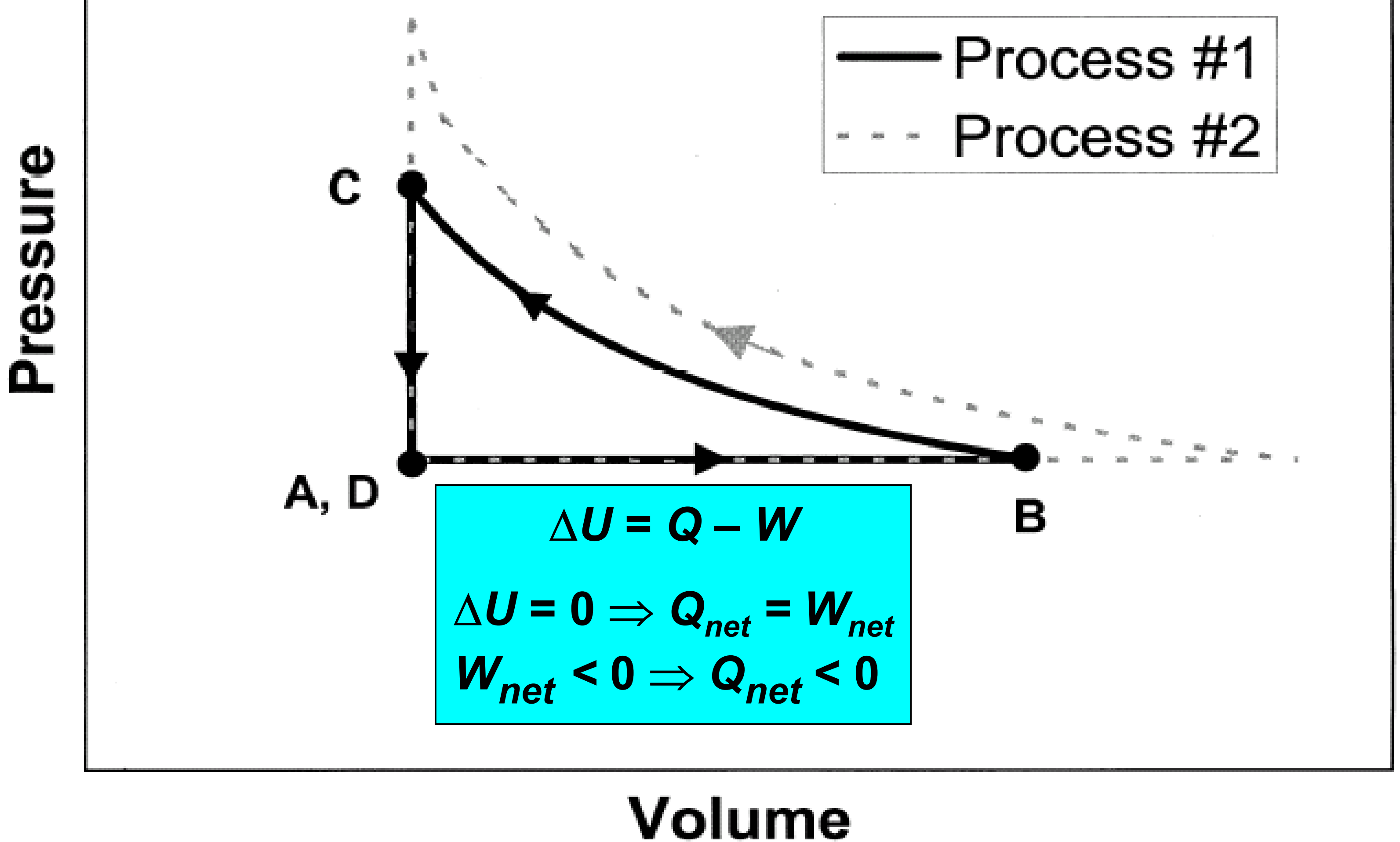
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

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

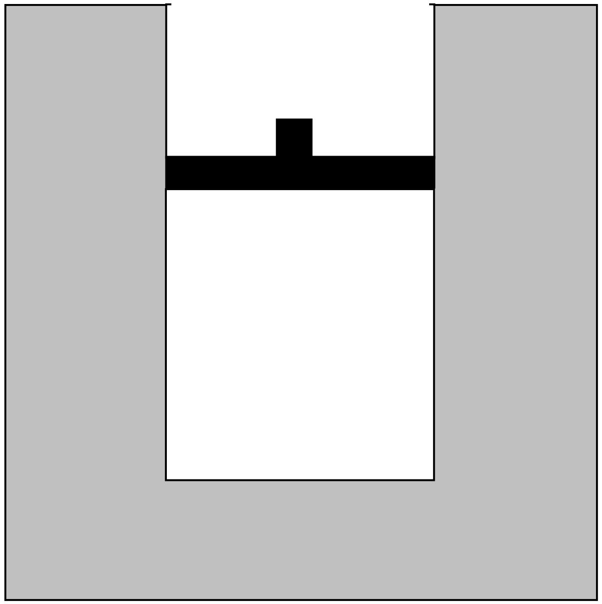
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

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

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



Time *D*

Piston in same position as at time *A*.

Temperature same as at time *A*.

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

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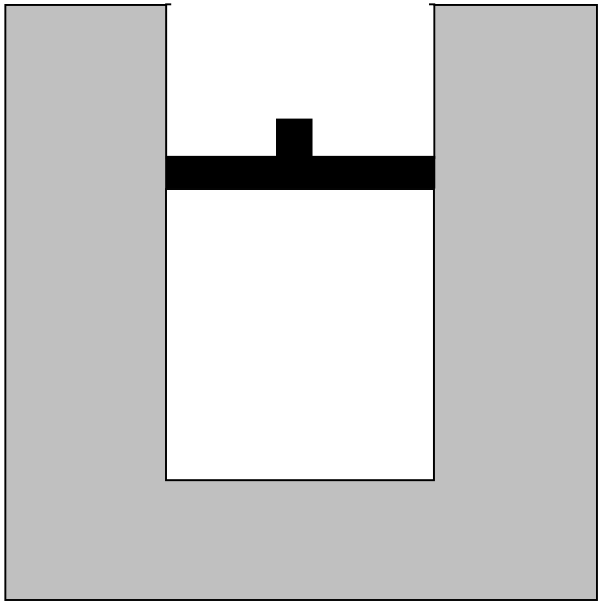

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Results on Interview Question #6 (ii)

$N = 32$

(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.*"

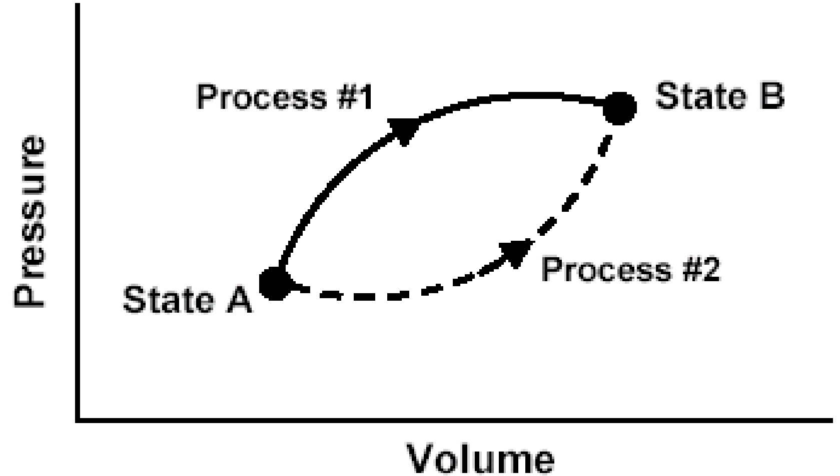
Most students thought that both Q_{net} and W_{net} are equal to zero

- 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. Failure to recognize "work" as a mechanism of energy transfer.
5. Confusion regarding isothermal processes and the thermal "reservoir."
6. Belief that net work done and net heat transferred during a cyclic process are zero.
7. 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.]

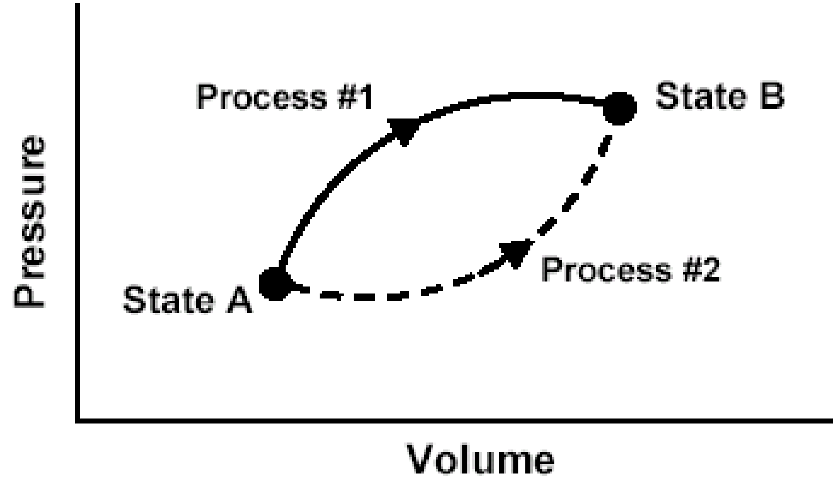
1. Is *W* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2? Explain.

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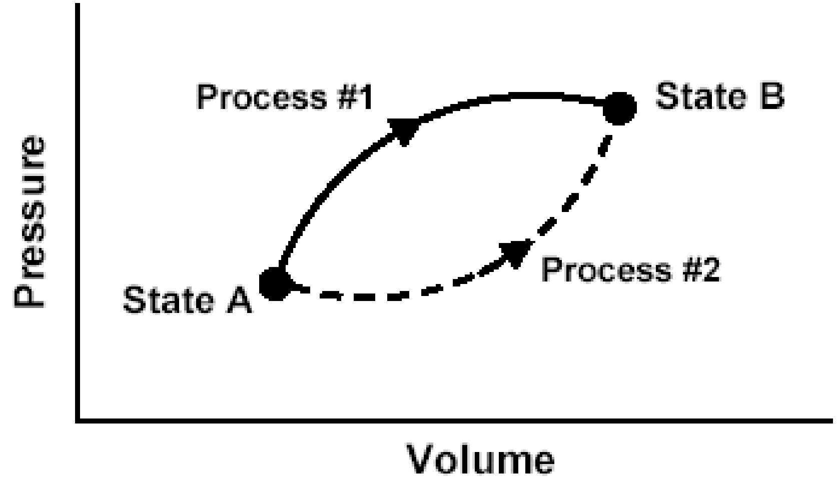
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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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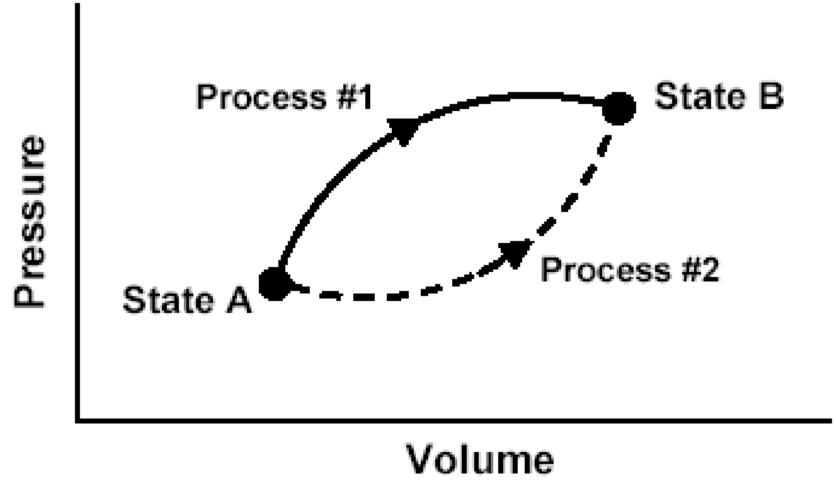

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Responses to Diagnostic Question #2
(Heat question)

	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}."

Responses to Diagnostic Question #2
(Heat question)

	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
$Q_1 > Q_2$	**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 $Q_1 > Q_2$.
- 13% of students in interview sample were able to use first law to correctly answer Question #6(ii).

→ **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

- Fewer than 20% of students overall could explain why $Q_1 > Q_2$.

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

Some Strategies for Instruction

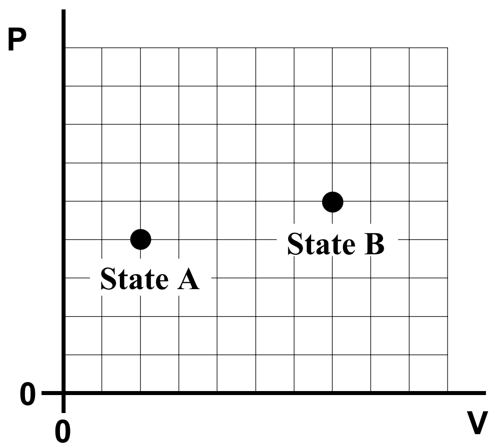
- Try to build on students' understanding of state-function concept.
- Focus on meaning of heat as ***transfer*** of energy, ***not*** quantity of energy residing in a system.
- Develop concept of work as energy transfer mechanism.
- Guide students to make increased use of *PV*-diagrams and similar representations.

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.

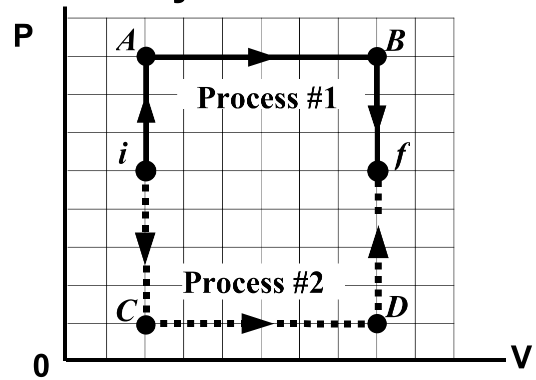


3. If a system starts with an initial internal energy of $U_{initial}$ and ends up with U_{final} some time later, we symbolize the *change* in the system's internal energy by ΔU and define it as follows: $\Delta U = U_{final} - U_{initial}$.

   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*?**
$i \to A$			
$A \to B$			
$B \to f$			
$i \to C$			
$C \to D$			
$D \to f$			

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.

Thermodynamics Curricular Materials

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

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

Summary

- Most students have substantial confusion regarding fundamental thermodynamic concepts even after completing general physics course.
  - *meaning of "heat" and "work" remains unclear*
- Failure to recognize "work" as energy-transfer mechanism lies at root of many difficulties.
  - *Loverude et al. showed that this was remnant of difficulties developed during mechanics instruction*
- Association of "heat" and "work" with "internal energy" [*it's all energy!*] leads to over-generalization of state-function concept.