Investigating and Addressing Learning Difficulties in Thermodynamics

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Collaborators

- Tom Greenbowe (Iowa State U. Chemistry)
- John Thompson (U. Maine Physics)
- Craig Ogilvie (ISU Physics)

Students

- Ngoc-Loan Nguyen (ISU M.S. 2003)
- Warren Christensen (ISU Ph.D. 2007)
- Tom Stroman (ISU physics graduate student)

Funding

- NSF Division of Undergraduate Education
- NSF Division of Physics

Research on the Learning and Teaching of Thermodynamics

- Investigate student learning of thermodynamics in physics and other fields
- Probe evolution of students' thinking from introductory through advanced-level course
- Develop research-based curricular materials

Phase One of Project:
Student Learning in Introductory Physics Course

- Probe students enrolled in second-semester calculus-based physics course (mostly engineering students).
  - Written diagnostic questions administered last week of class.
  - Detailed interviews carried out with volunteers.

Phase Two of Project:

Student Learning in Upper-Level Physics Course

- **Topics:** Approximately equal balance between classical macroscopic thermodynamics, and statistical thermodynamics

- **Students enrolled** [$N_{initial}$ = 14 (*2003*) and 19 (*2004*)]

  ≈ 90% were physics majors or physics/engineering double majors

  ≈ 90% were juniors or above

All students had previously studied thermodynamics (some at the advanced level)

Performance Comparison: Upper-level vs. Introductory Students

- Diagnostic questions given to students in introductory calculus-based course *after* instruction was complete:
  - 1999-2001: 653 students responded to written questions
  - 2002: 32 self-selected, high-performing students participated in one-on-one interviews
- Written pre-test questions given to Upper-level students on first day of class

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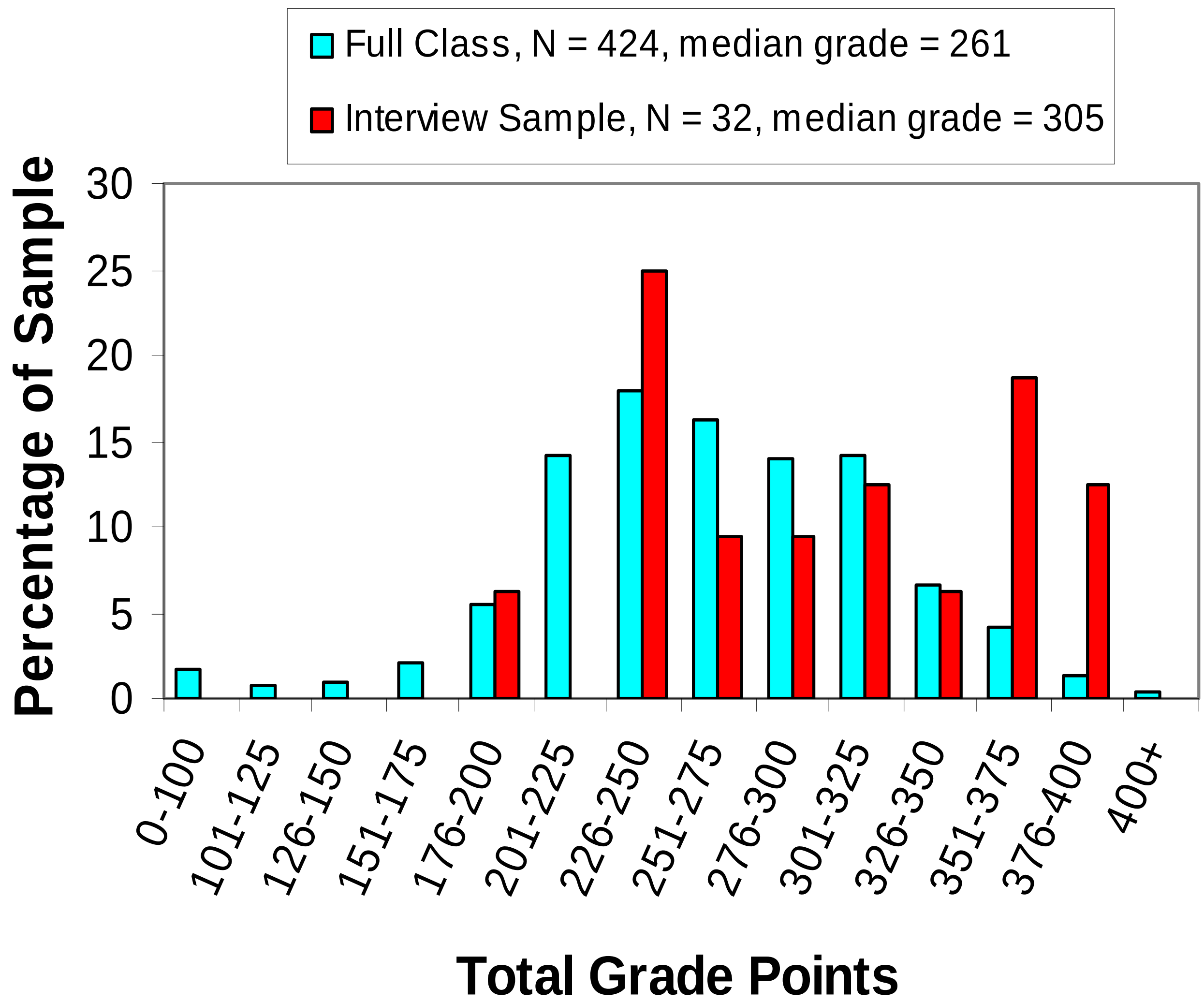
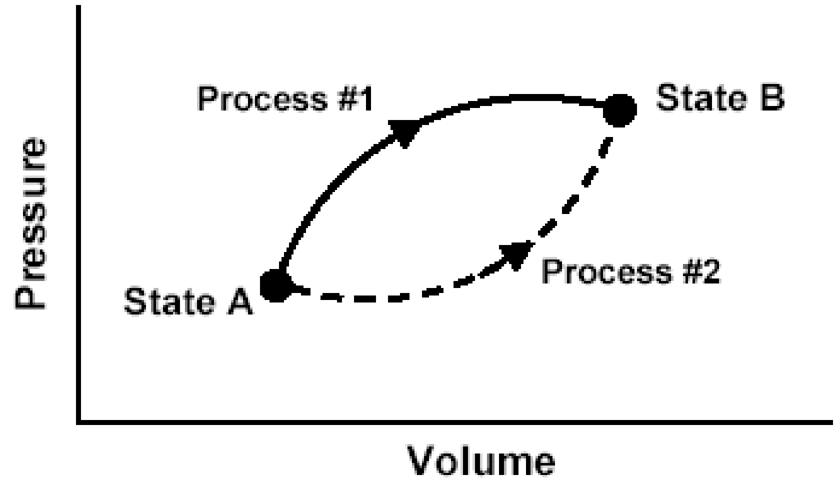
Grade Distributions: Interview Sample vs. Full Class



***Interview Sample*:**

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

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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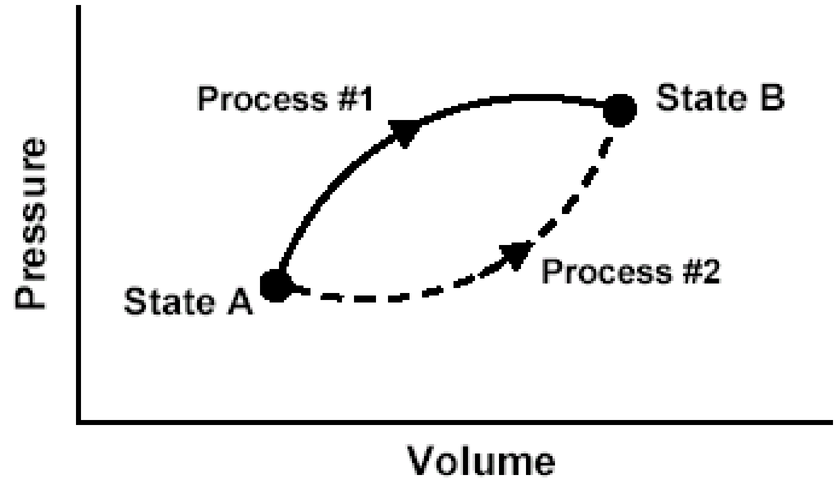

[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

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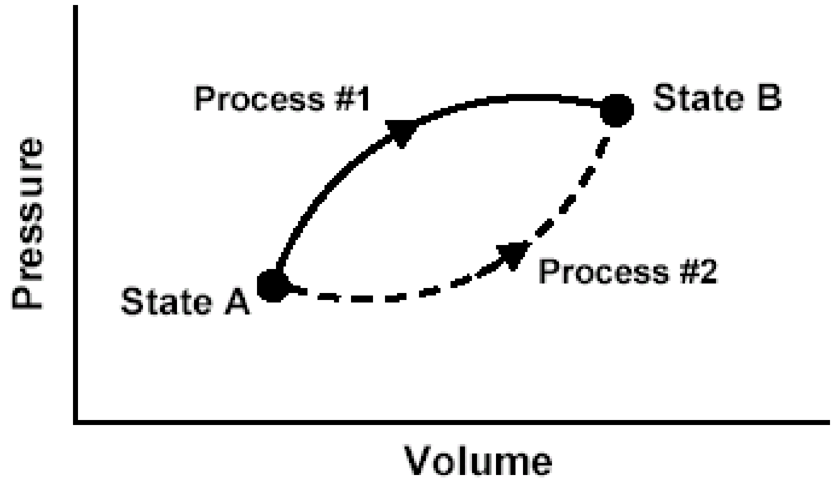

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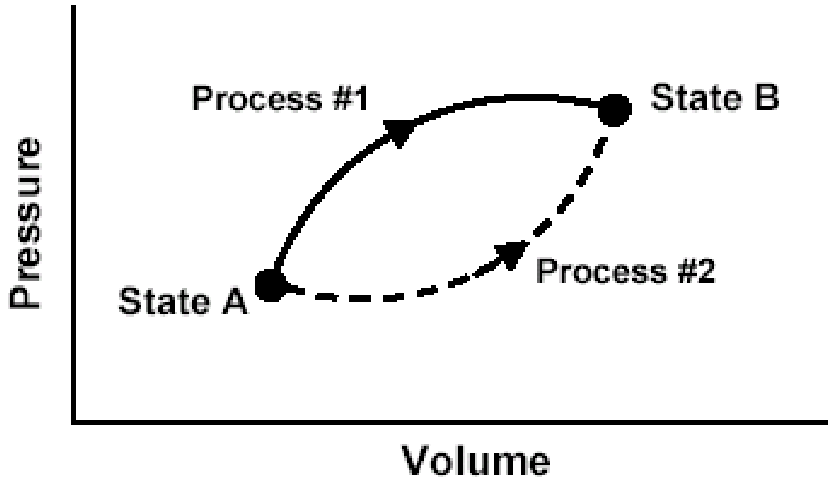

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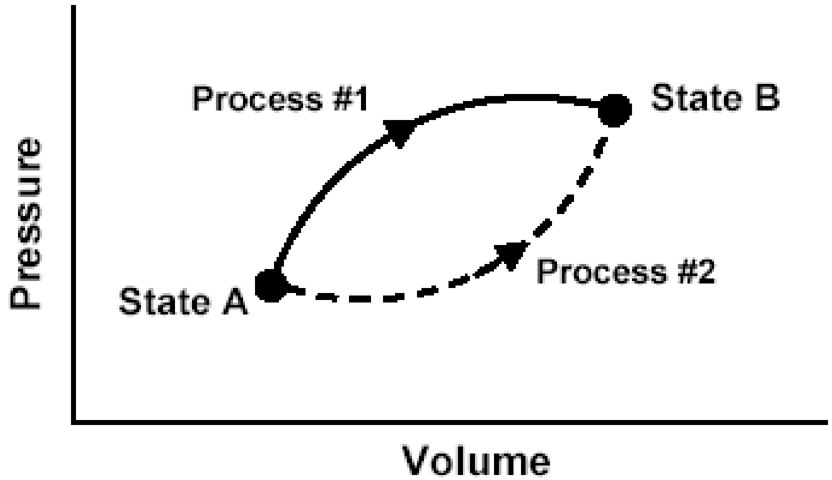

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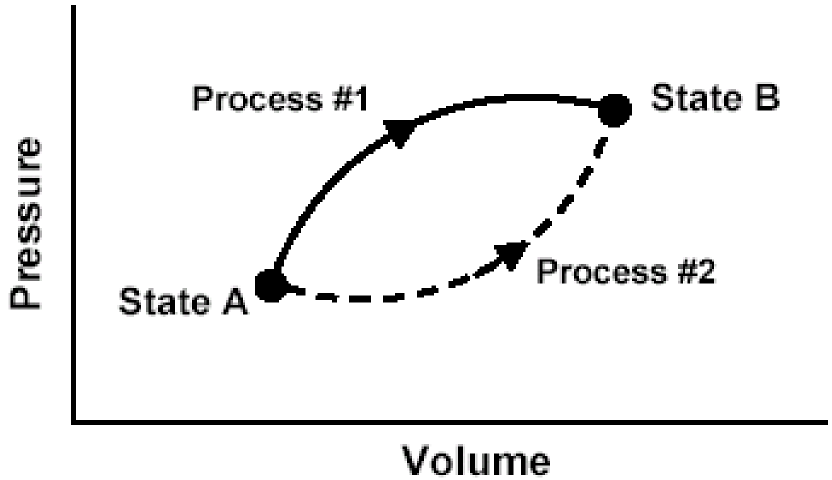

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Responses to Diagnostic Question #1

(Work question)

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**	**2002** **Introductory Physics** **(Post-test)** **Interview Sample** **(*N*=32)**	**2004** **Upper- Level** **(Pretest)** **(*N*=19)**
$W_1 > W_2$			
$W_1 = W_2$			
$W_1 < W_2$			

Responses to Diagnostic Question #1

(Work question)

$W_1 = W_2$			

Responses to Diagnostic Question #1
(Work question)

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**		
$W_1 = W_2$	**30%**		

Responses to Diagnostic Question #1

(Work question)

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	**2002** Introductory Physics (Post-test) Interview Sample (*N*=32)	
$W_1 = W_2$	**30%**	**22%**	

Responses to Diagnostic Question #1

(Work question)

	1999-2001 Introductory Physics (Post-test) Written Sample (N=653)	**2002** Introductory Physics (Post-test) Interview Sample (N=32)	**2003** Upper-level Course (Pretest) (N=14)
$W_1 = W_2$	30%	22%	20%

Responses to Diagnostic Question #1
(Work question)

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$W_1 = W_2$	**30%**	**22%**	**20%**

About one-fifth of Upper-level students believe work done is equal in both processes

Explanations Given by Upper-Level Students to Justify $W_1 = W_2$

- "*Equal, path independent*."

- "*Equal, the work is the same regardless of path taken*."

Some students come to associate work with phrases only used in connection with state functions.

Explanations similar to those offered by introductory students

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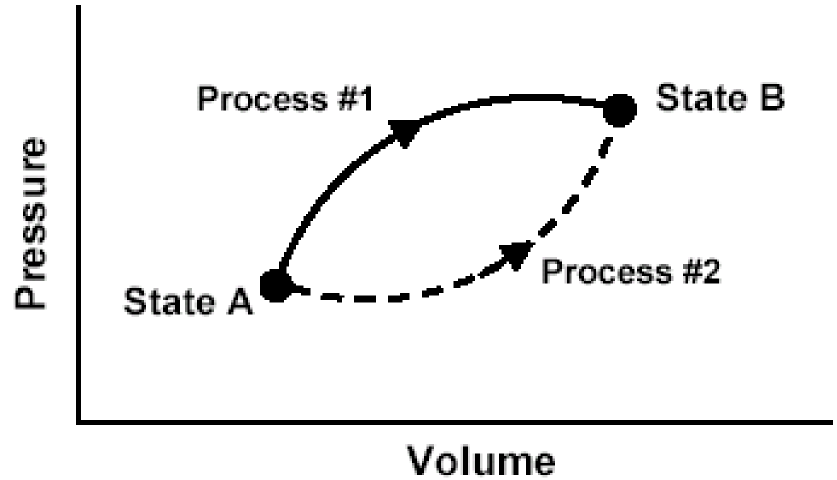

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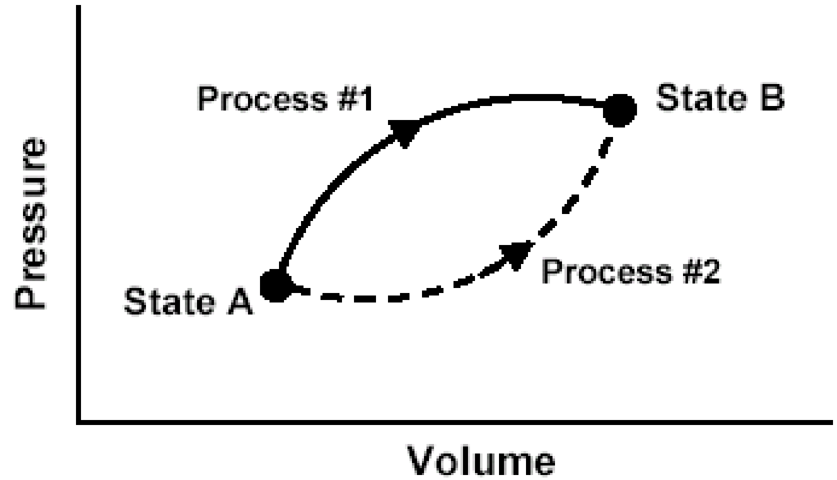

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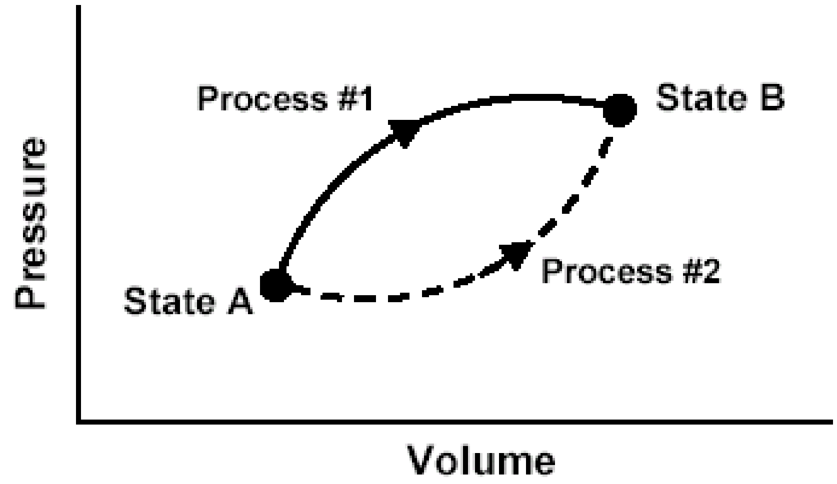
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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



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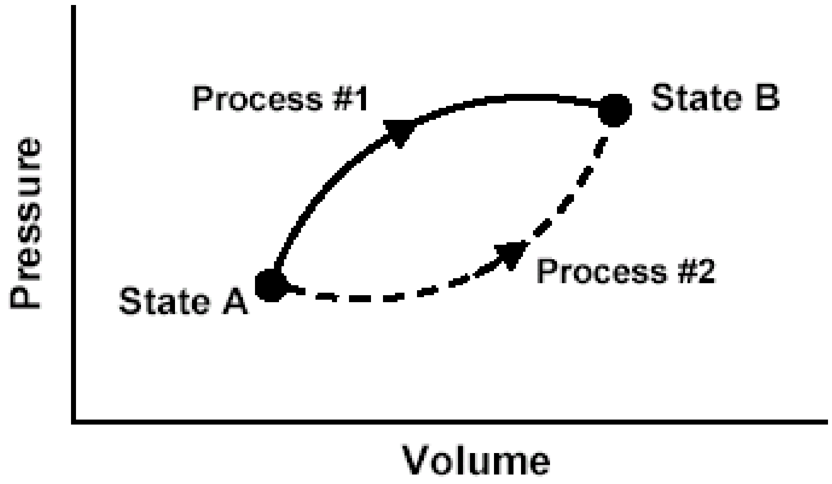
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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

Responses to Diagnostic Question #2
(Heat question)

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	**2002** Introductory Physics (Post-test) Interview Sample (*N*=32)	**2004** Upper-level Course (Pretest) (*N*=19)
$Q_1 > Q_2$			
$Q_1 = Q_2$			
$Q_1 < Q_2$			

Responses to Diagnostic Question #2

(Heat question)

$\boldsymbol{Q_1 = Q_2}$			

Responses to Diagnostic Question #2
(Heat question)

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**		
$Q_1 = Q_2$	**38%**		

Responses to Diagnostic Question #2
(Heat question)

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**	**2002** **Introductory Physics** **(Post-test)** **Interview Sample** **(*N*=32)**	
$Q_1 = Q_2$	**38%**	**47%**	

Responses to Diagnostic Question #2
(Heat question)

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**	**2002** **Introductory Physics** **(Post-test)** **Interview Sample** **(*N*=32)**	**2003-4** **Upper-level Course** **(Pretest)** **(*N*=33)**
$Q_1 = Q_2$	**38%**	**47%**	**30%**

Explanations Given by Upper-Level Students to Justify $Q_1 = Q_2$

- "*Equal. They both start at the same place and end at the same place*."
- "*The heat transfer is the same because they are starting and ending on the same isotherm*."

➢ **Many Upper-level students stated or implied that heat transfer is independent of process, similar to claims made by introductory students.**

Responses to Diagnostic Question #2

(Heat question)

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$Q_1 > Q_2$			
$Q_1 = Q_2$			
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Responses to Diagnostic Question #2

(Heat question)

$Q_1 > Q_2$			
[Correct answer]			

Responses to Diagnostic Question #2
(Heat question)

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**		
$Q_1 > Q_2$	**45%**		

Responses to Diagnostic Question #2

(Heat question)

	1999-2001 Introductory Physics (Post-test) Written Sample (N=653)	**2002** Introductory Physics (Post-test) Interview Sample (N=32)	
$Q_1 > Q_2$	**45%**	**34%**	

Responses to Diagnostic Question #2

(Heat question)

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	**2002** Introductory Physics (Post-test) Interview Sample (*N*=32)	**2003** Upper-level Course (Pretest) (*N*=14)
$Q_1 > Q_2$	**45%**	**34%**	**35%**

Responses to Diagnostic Question #2
(Heat question)

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**	**2002** **Introductory Physics** **(Post-test)** **Interview Sample** **(*N*=32)**	**2003** **Upper-level Course** **(Pretest)** **(*N*=14)**
$Q_1 > Q_2$	**45%**	**34%**	**35%**
Correct or partially correct explanation	**11%**	**19%**	**30%**

Responses to Diagnostic Question #2

(Heat question)

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(Heat question)

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Performance of upper-level students significantly better than introductory students in *written* sample

Cyclic Process Questions

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

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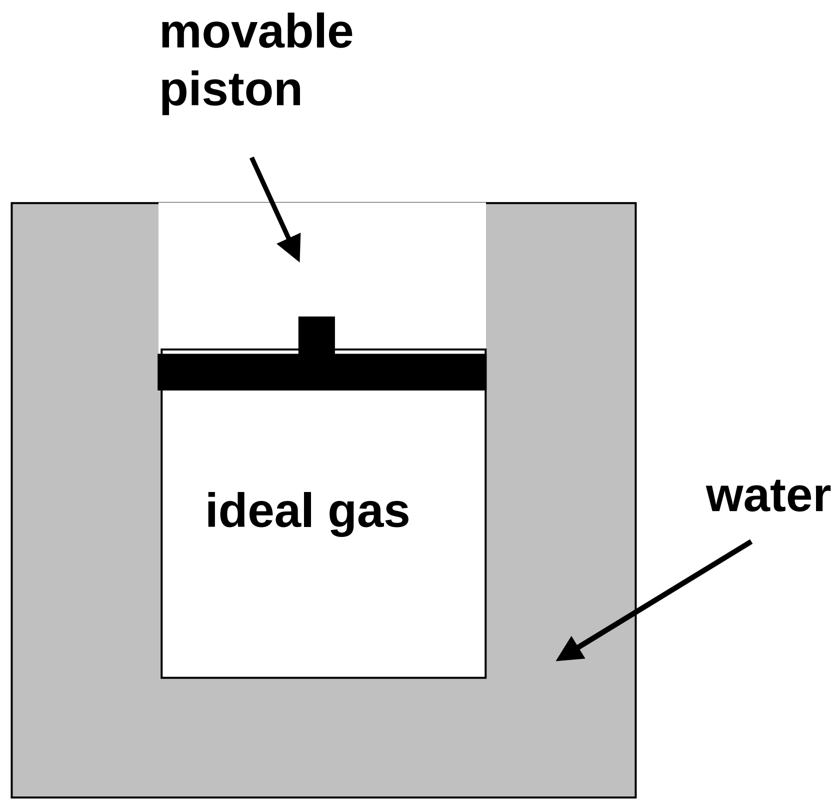
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

Cyclic Process Questions

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

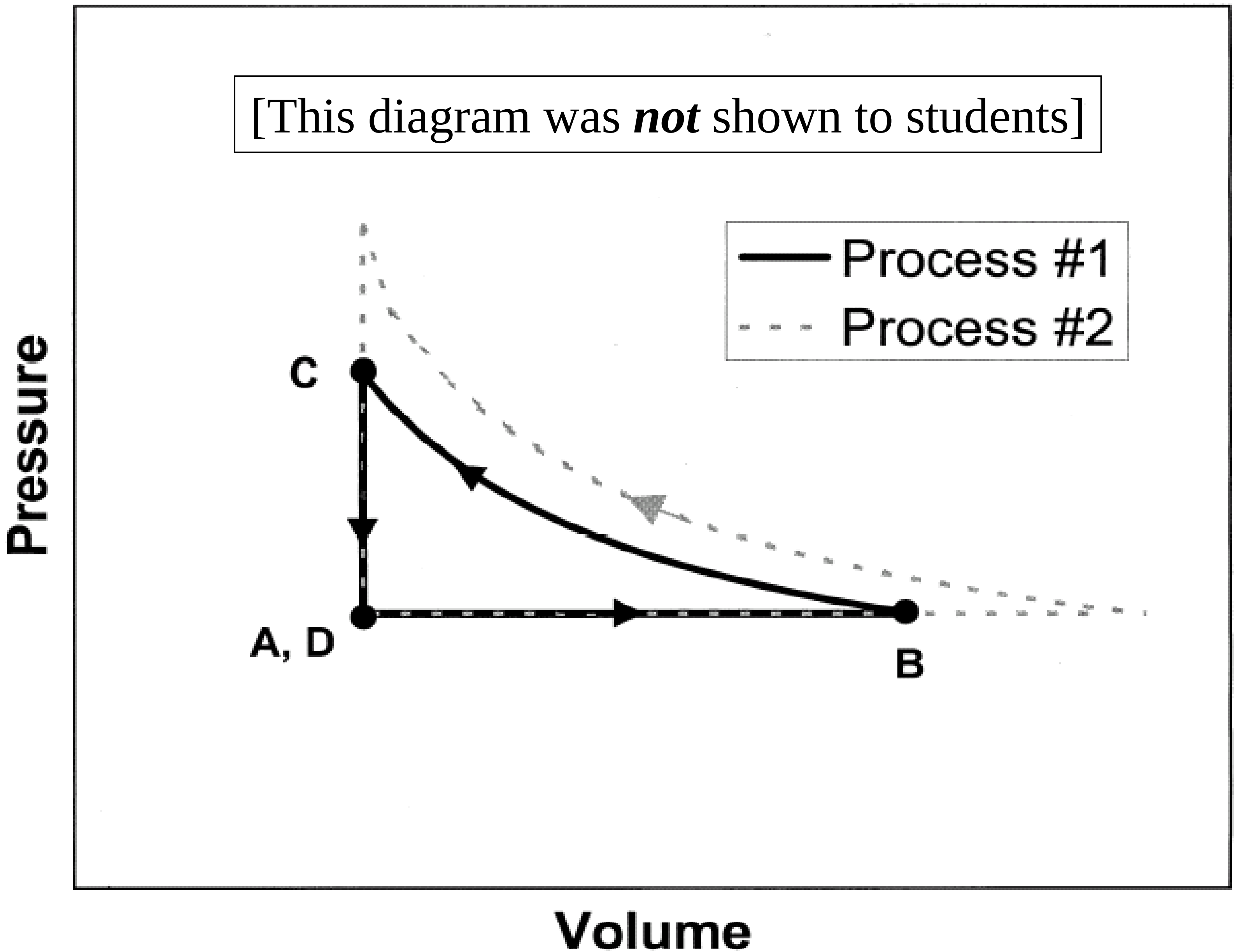
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

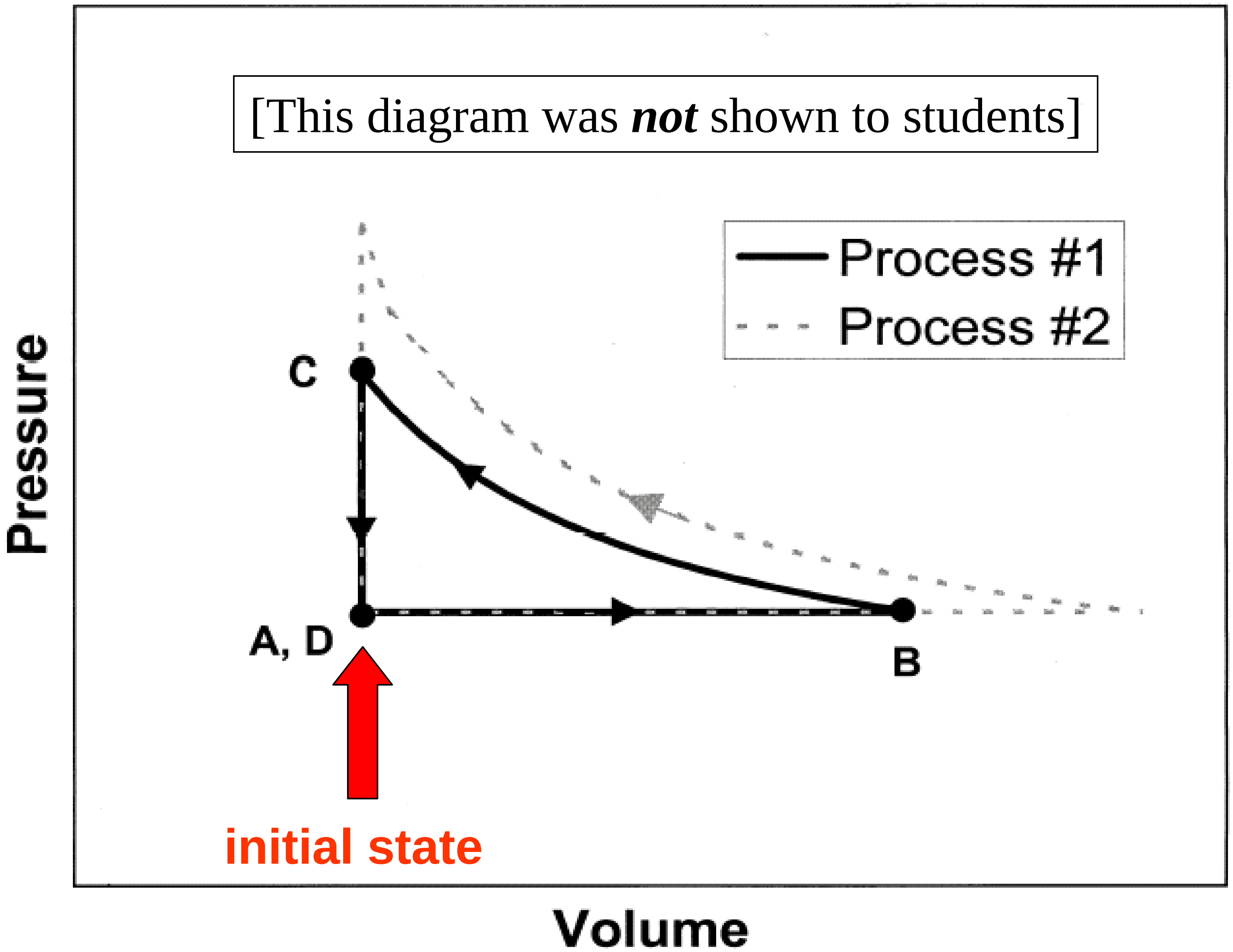
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature



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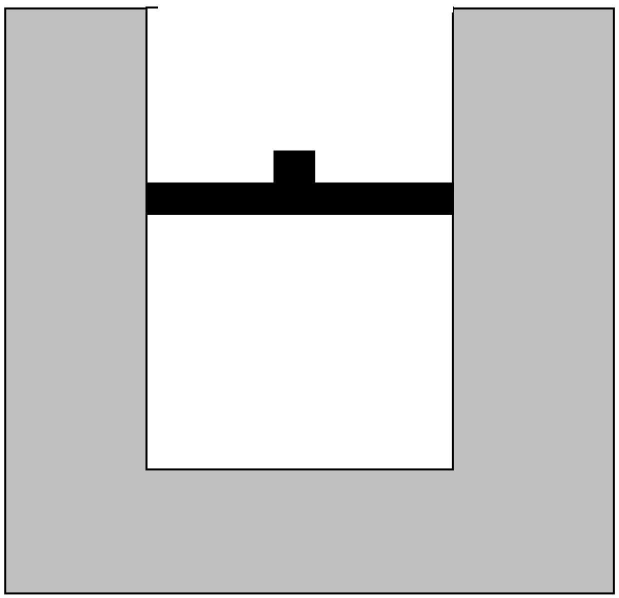
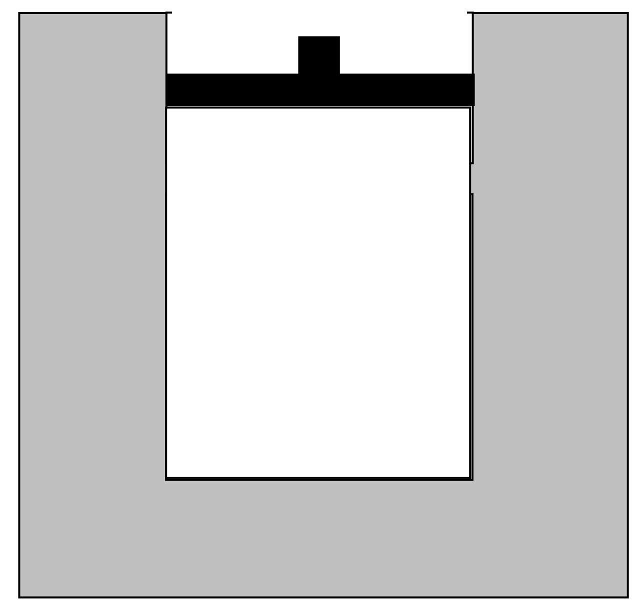
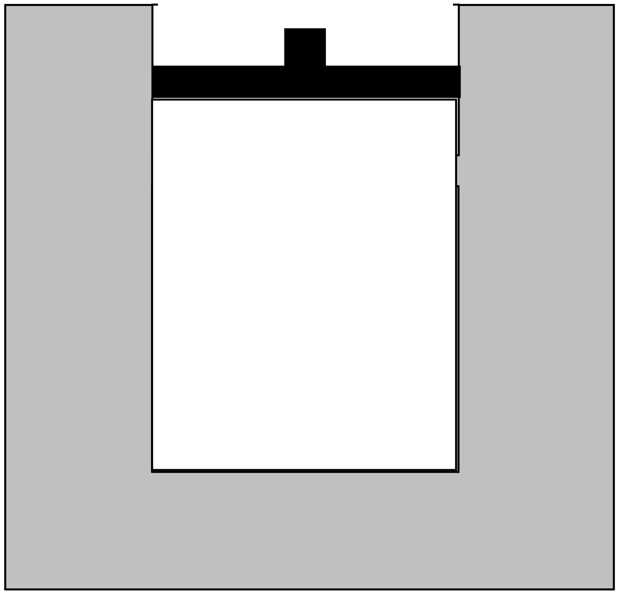
Process #1
Process #2
C
A, D
B
initial state
Pressure
Volume

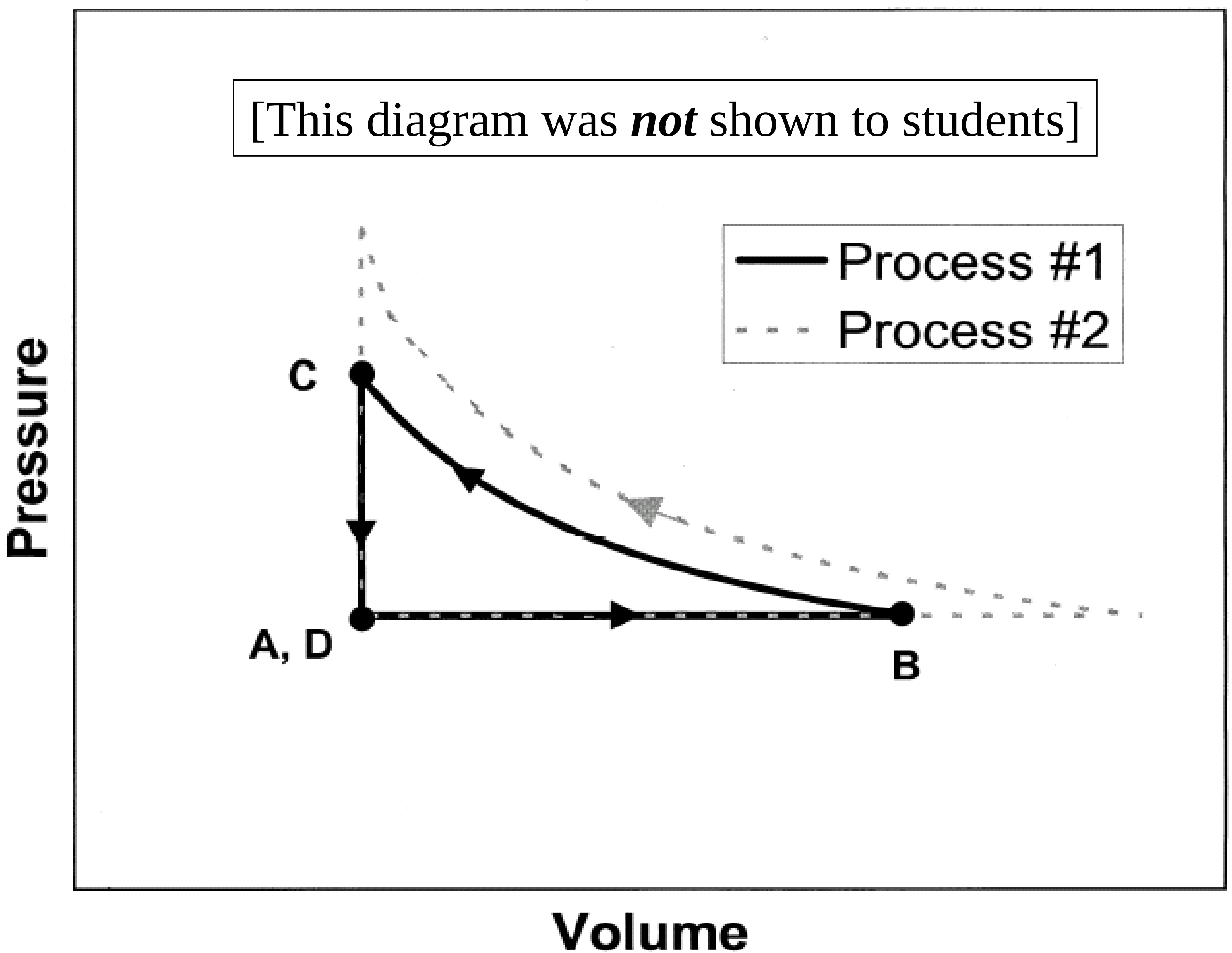
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.





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





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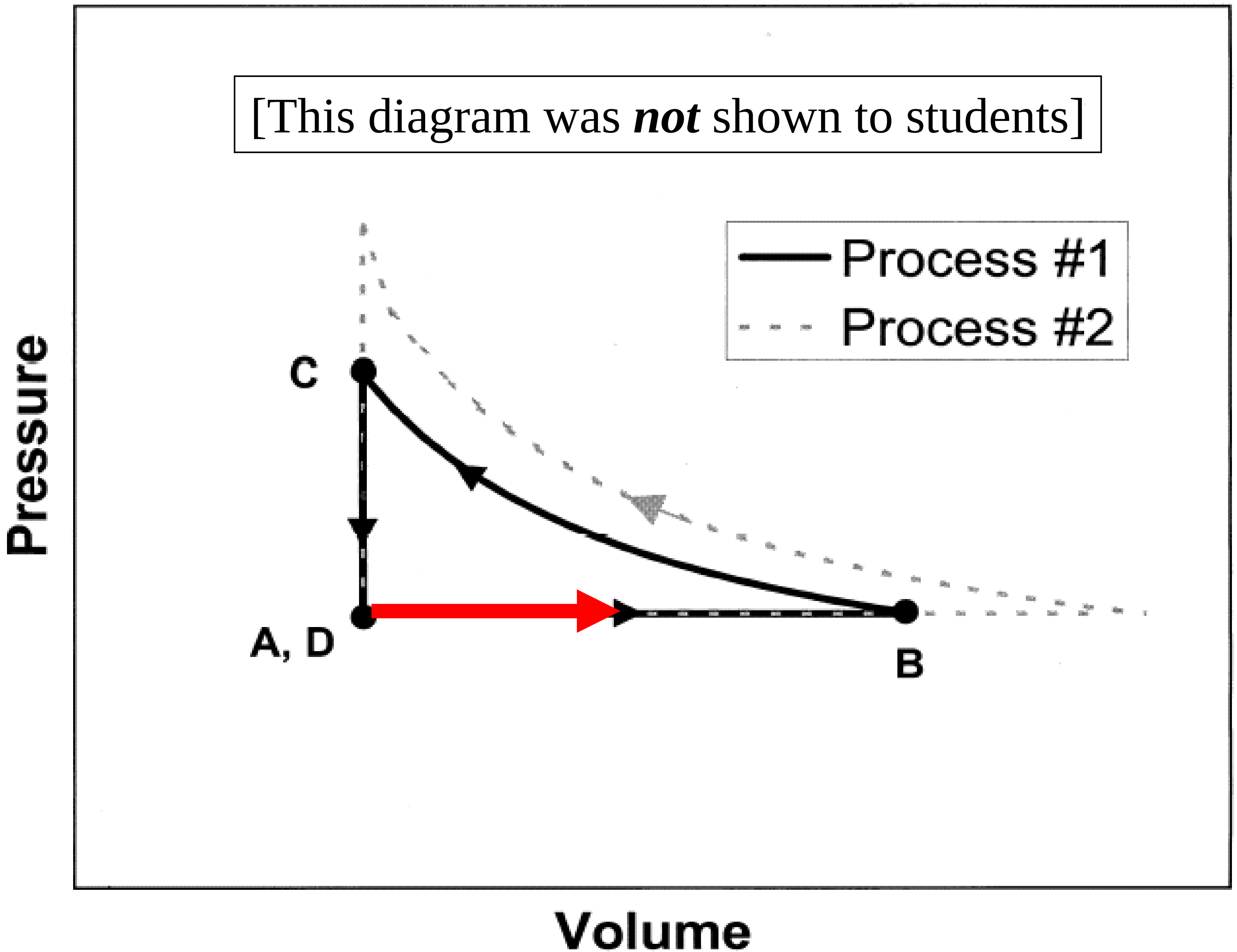
Process #1
Process #2
C
A, D
B
Pressure
Volume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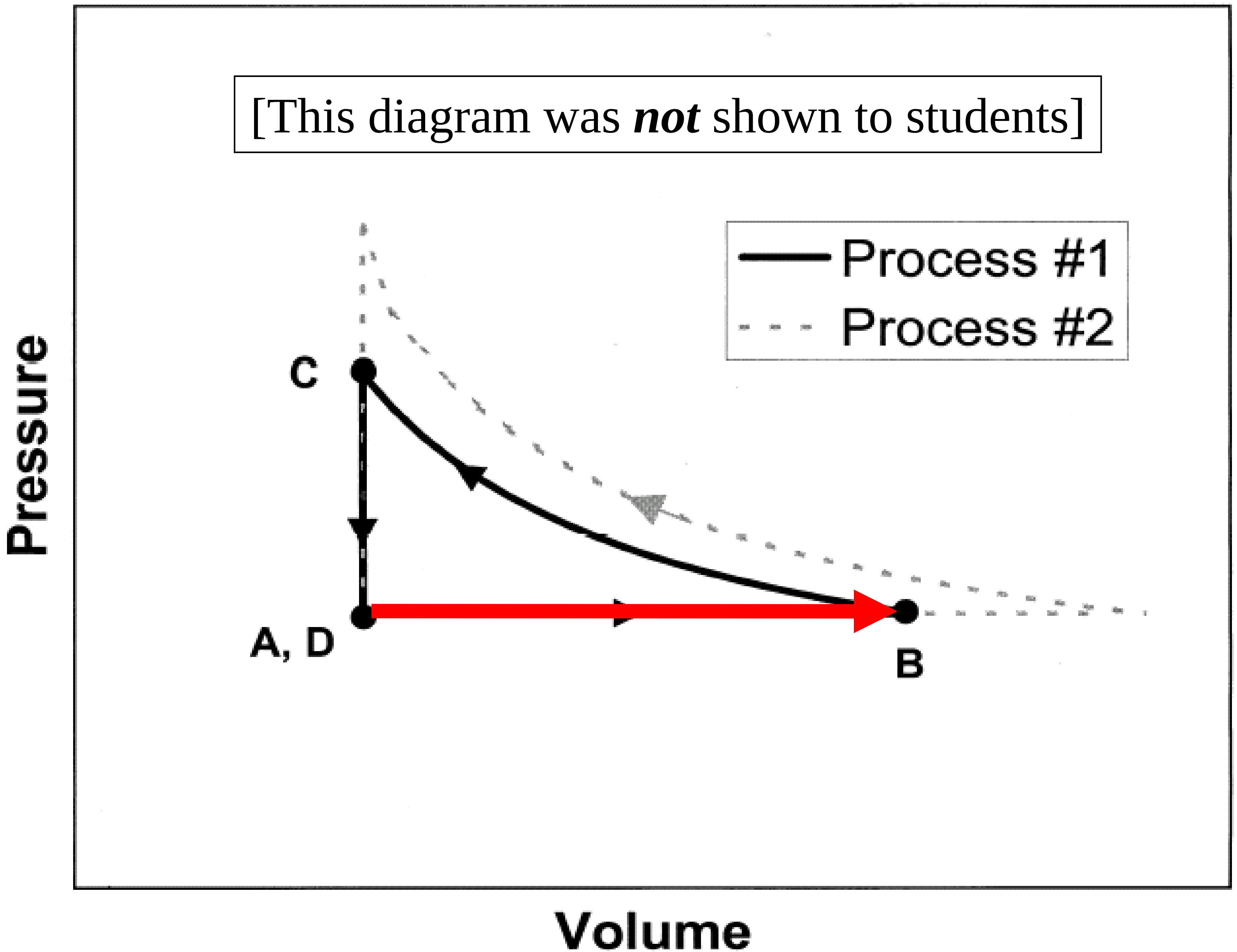
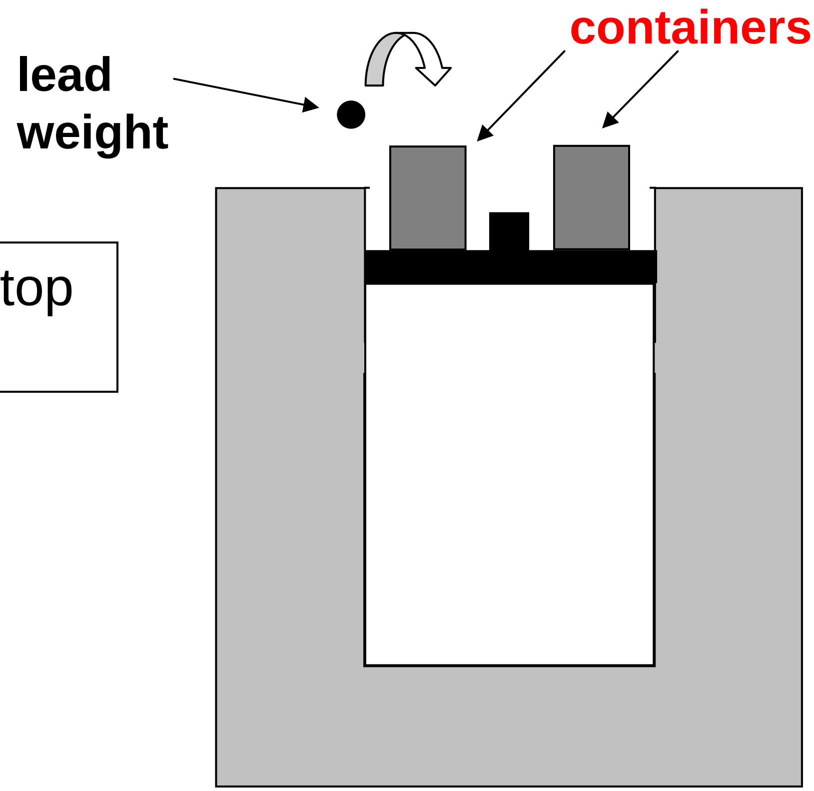
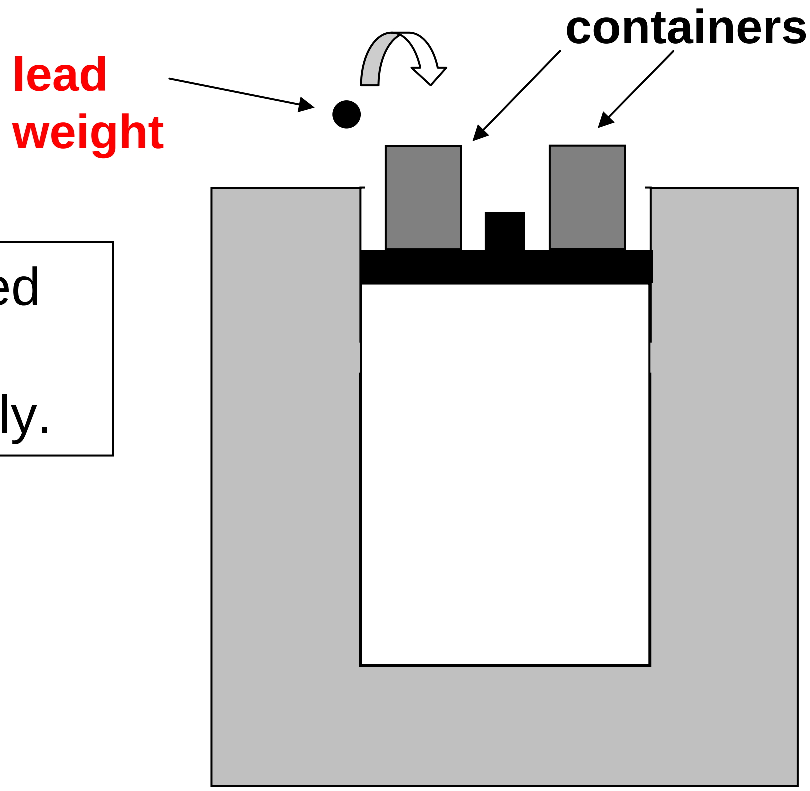
Process #1
Process #2
C
A, D
B
Pressure
Volume

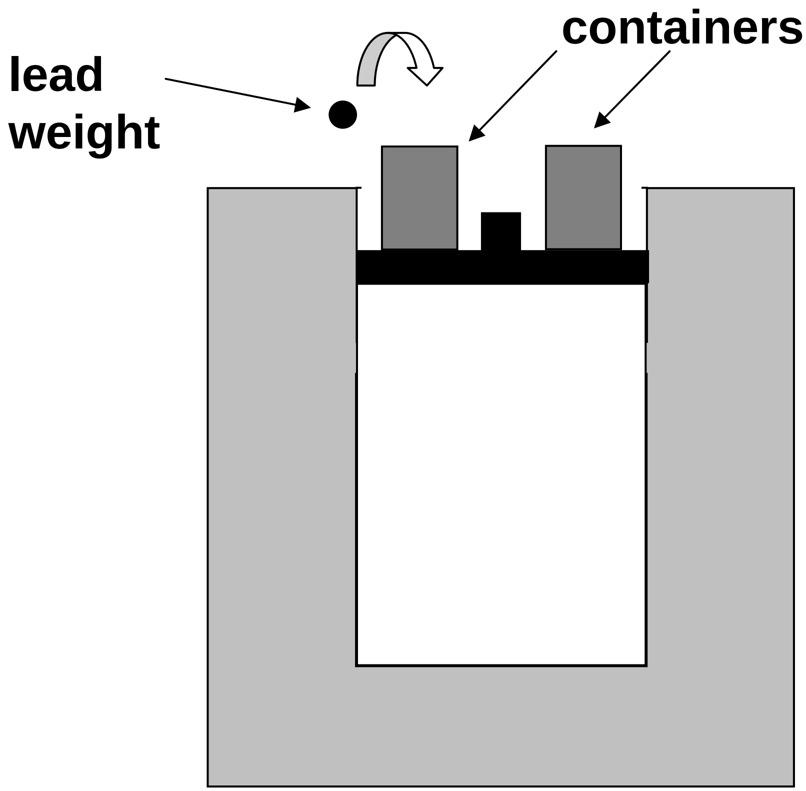

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

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

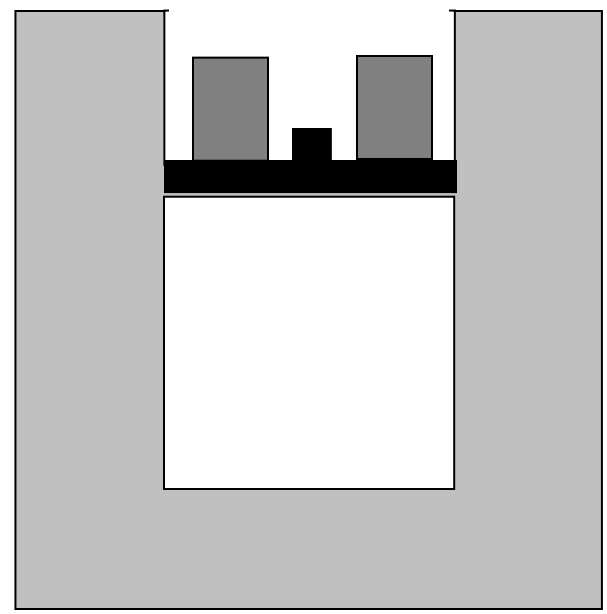


Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly.

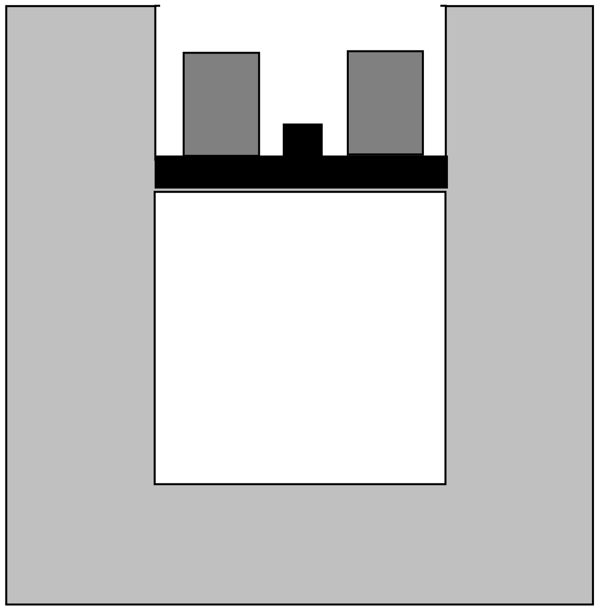




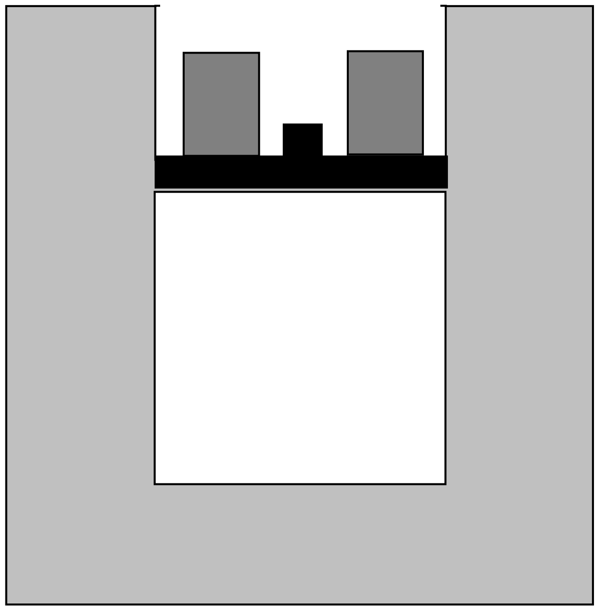
lead
weight
containers

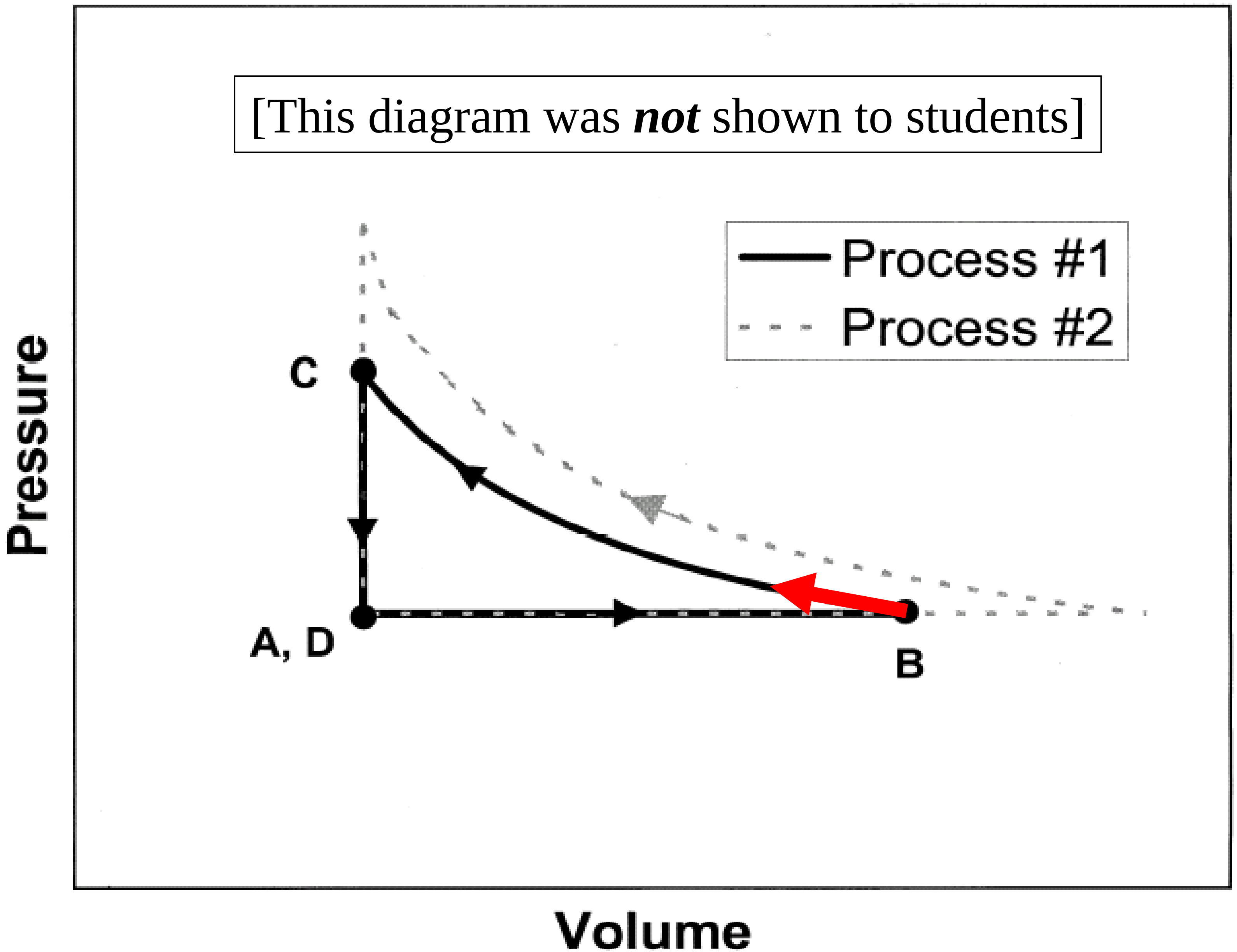


While this happens the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*.



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*** .

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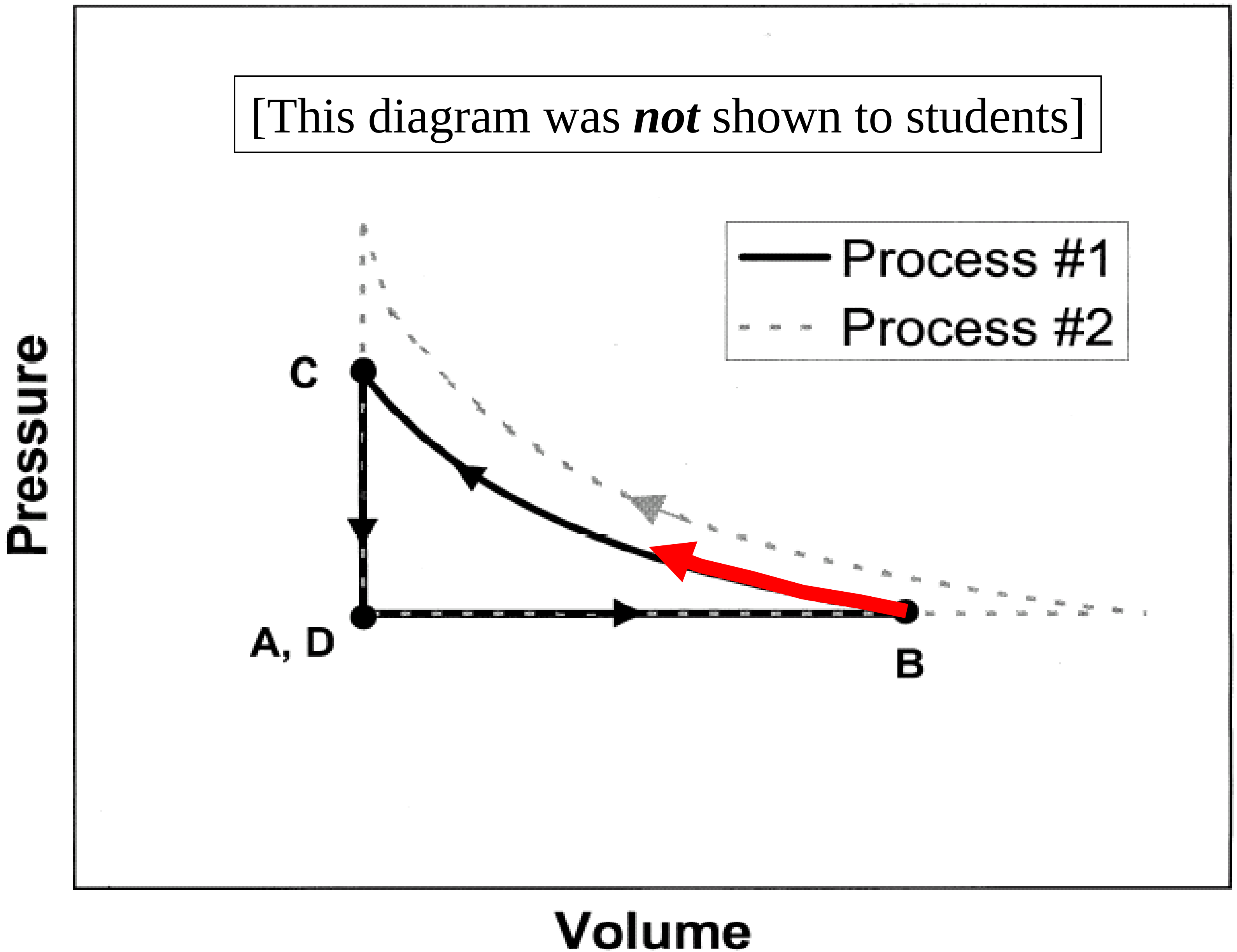
Process #1
Process #2
C
A, D
B
Pressure
Volume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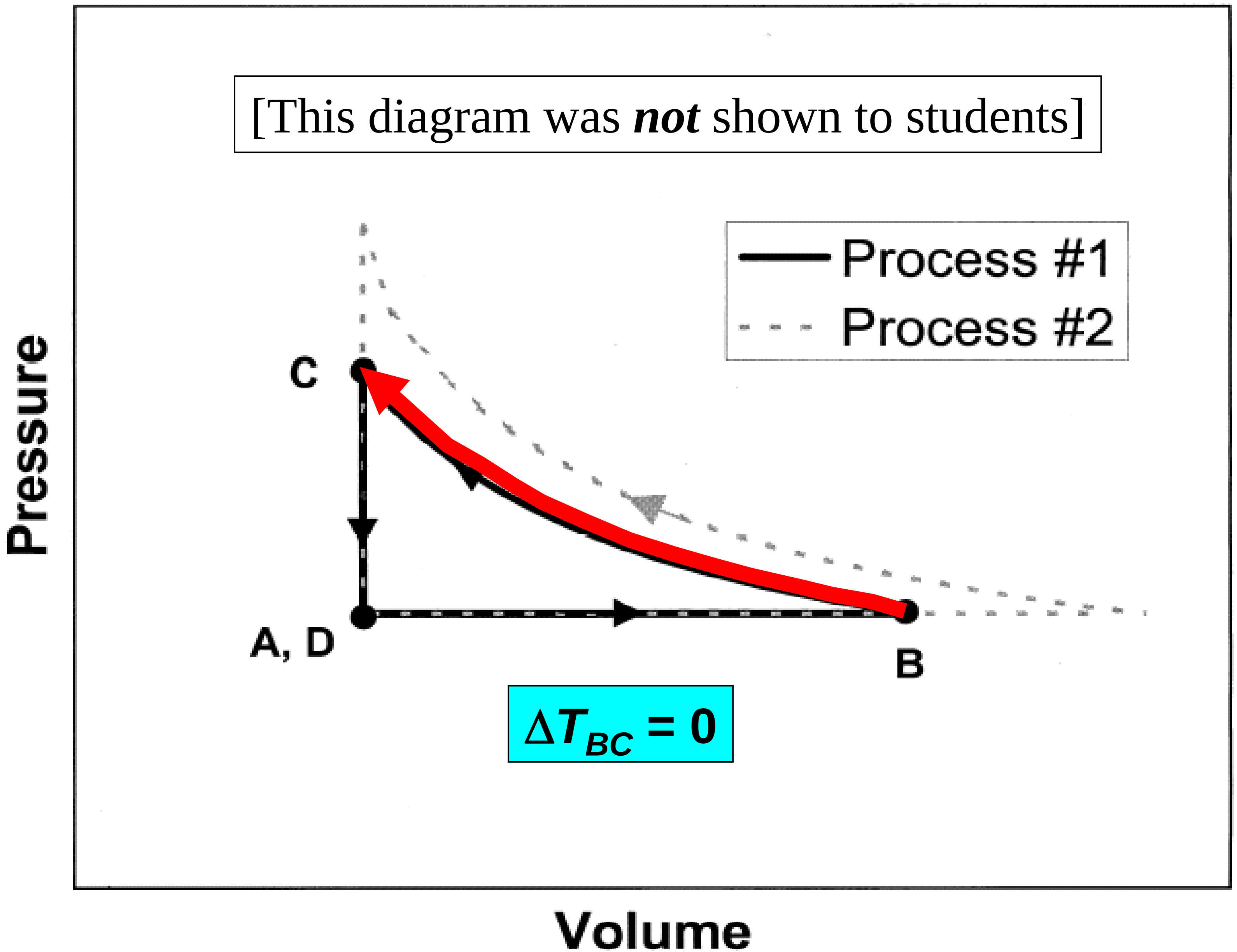
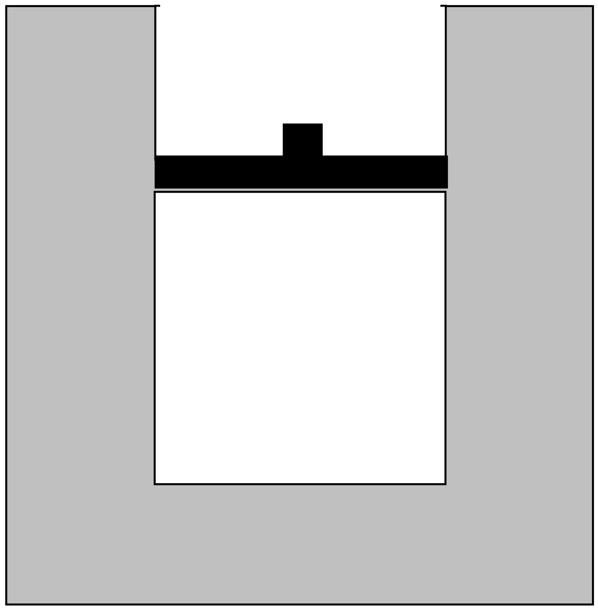
A, D
B
Pressure
Volume

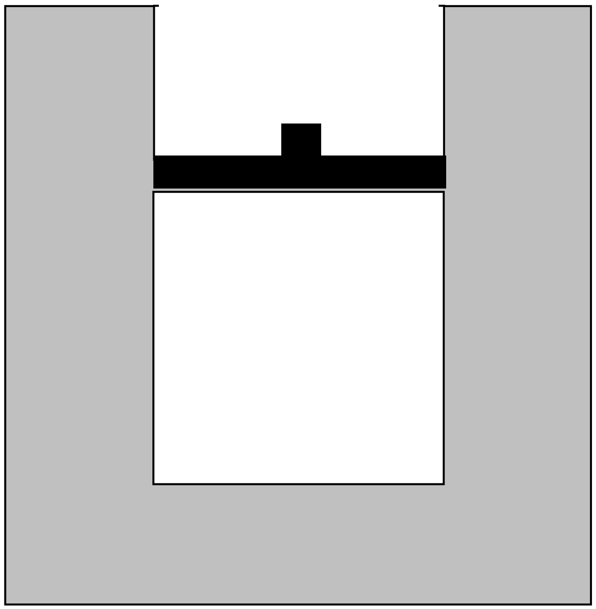


[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
$\Delta T_{BC} = 0$
Pressure
Volume

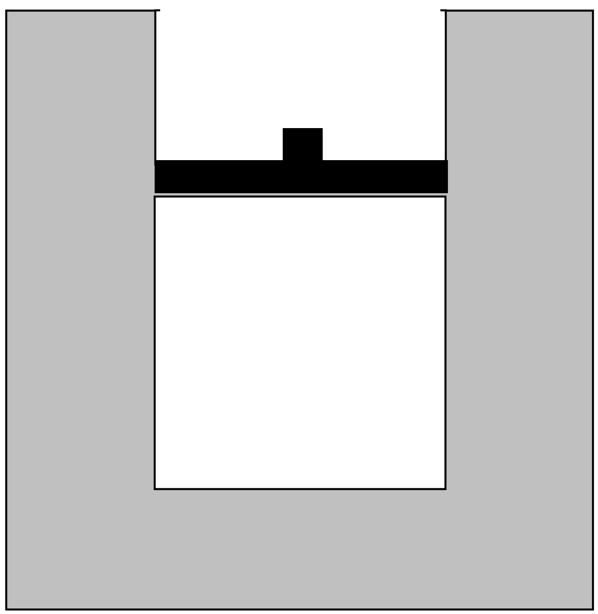
Now, the piston is locked into place so it *cannot move*, and the weights are removed from the piston.



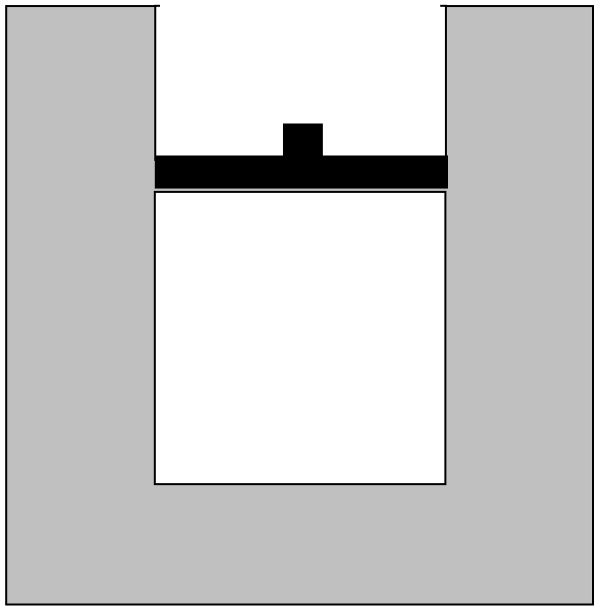
The system is left to sit in the room for many hours.

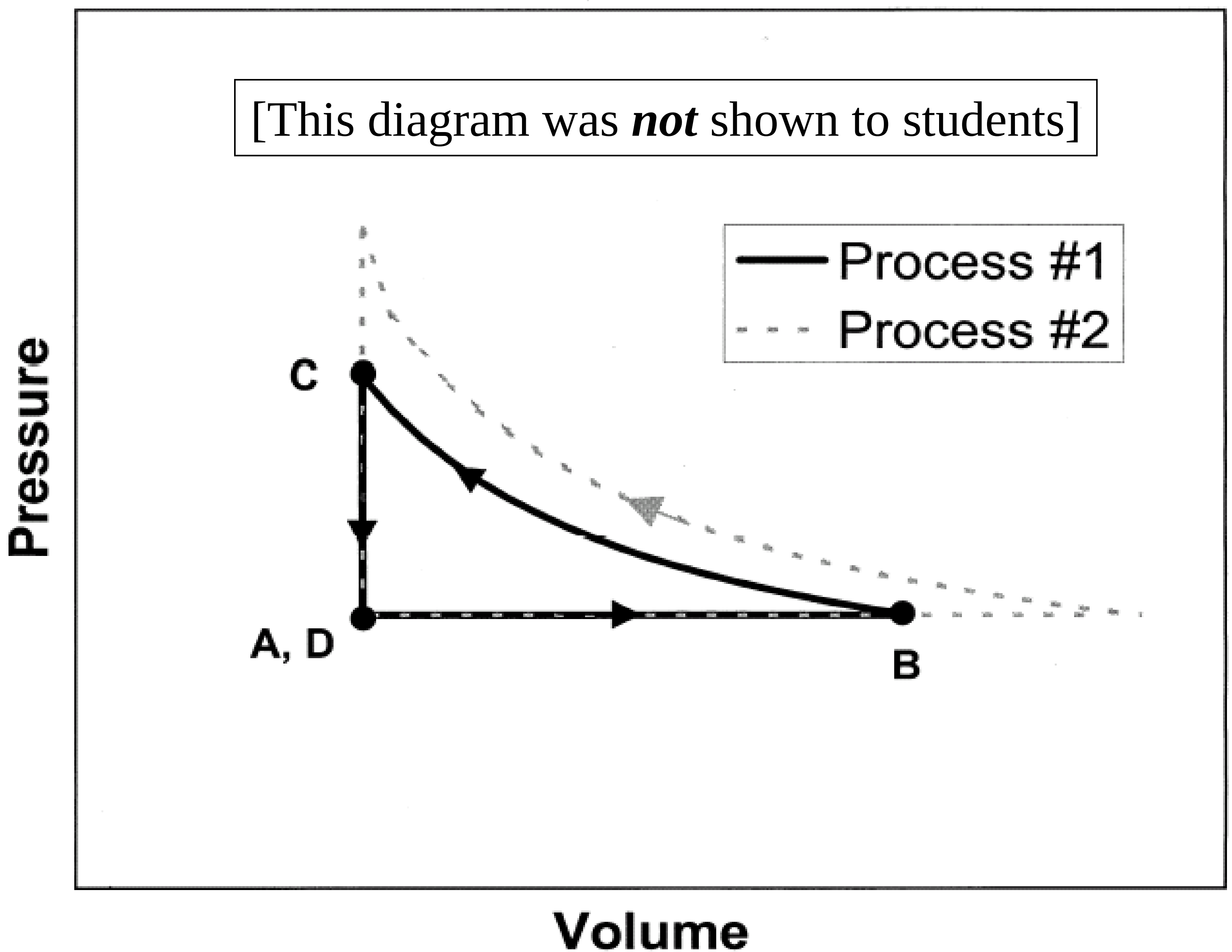


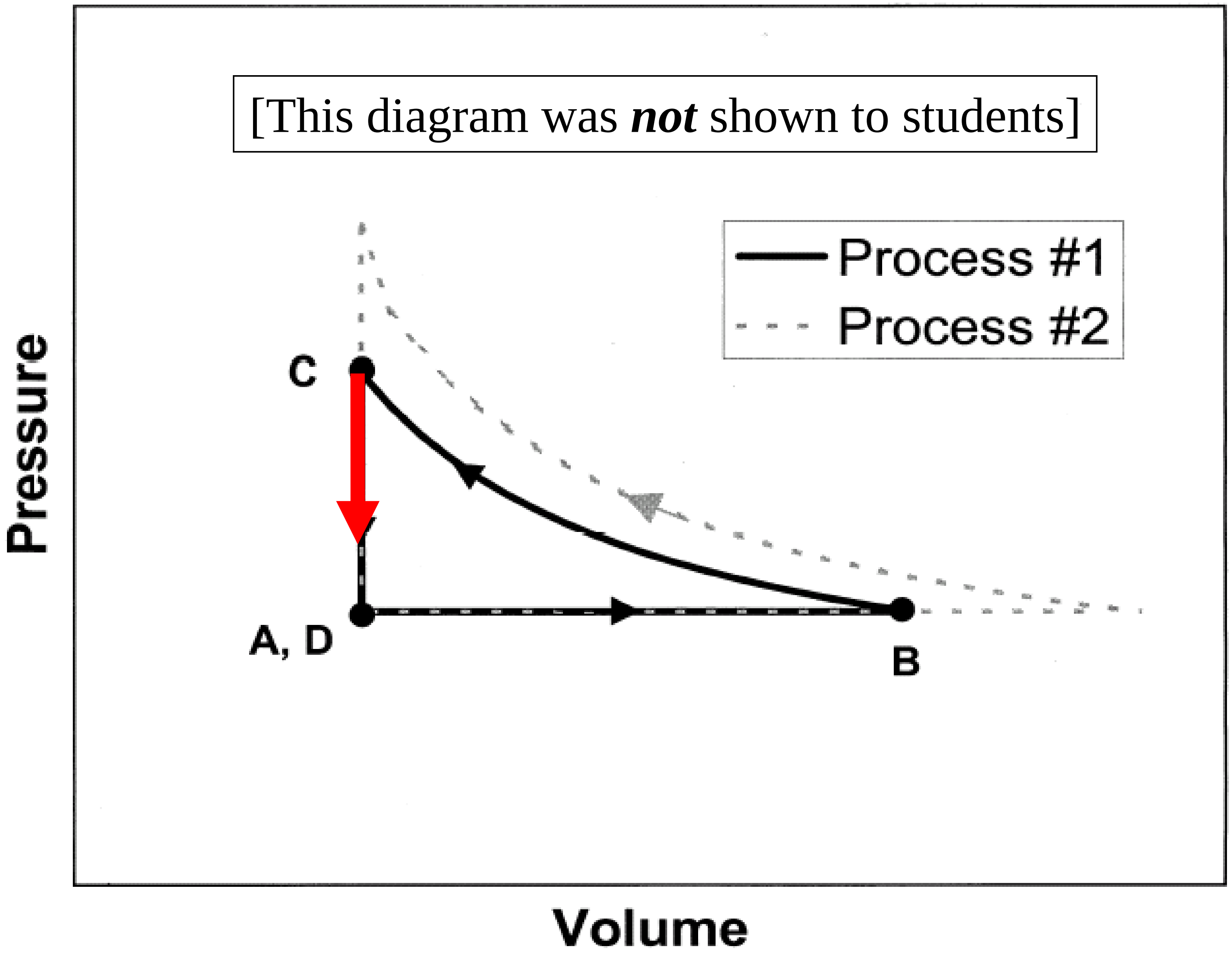
Eventually the entire system cools back down to the same room temperature it had at time ***A.***

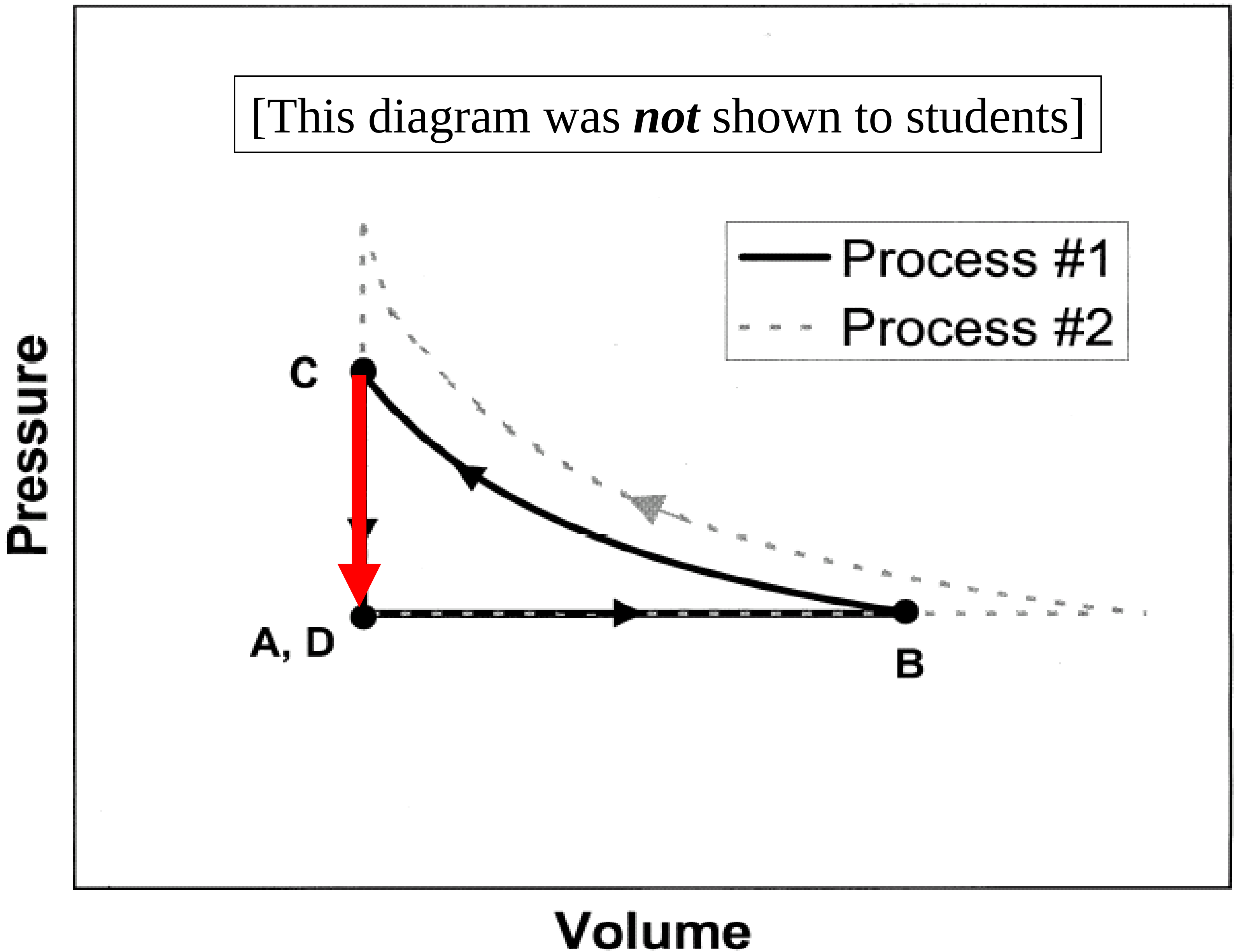


After cooling is complete, it is time ***D.***

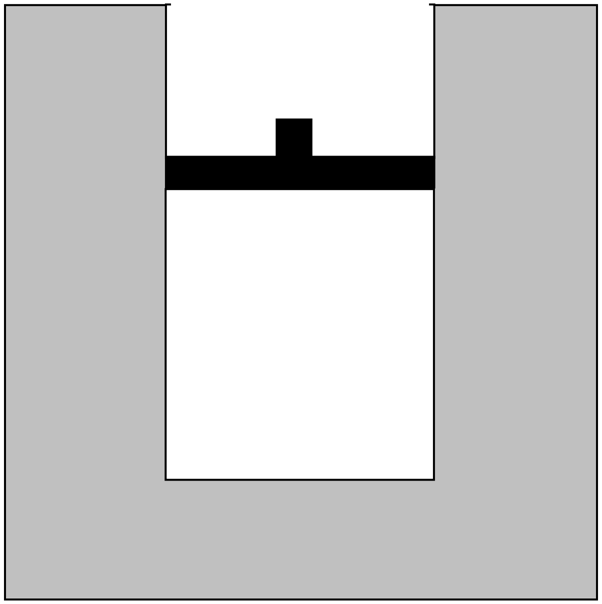



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume


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



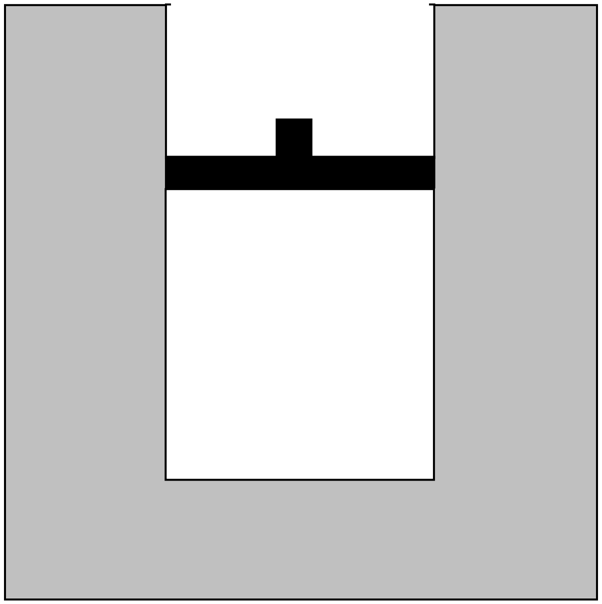
[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



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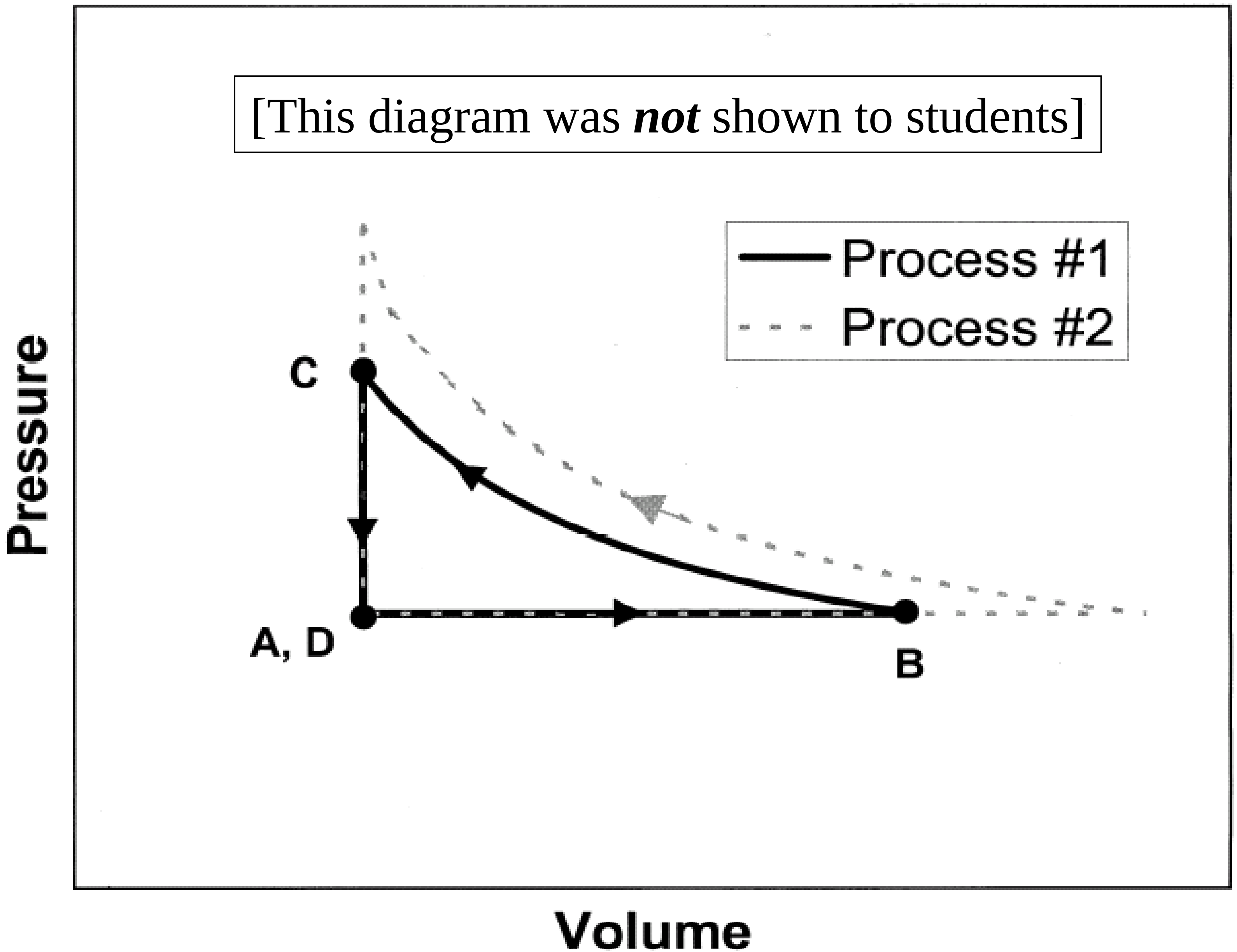
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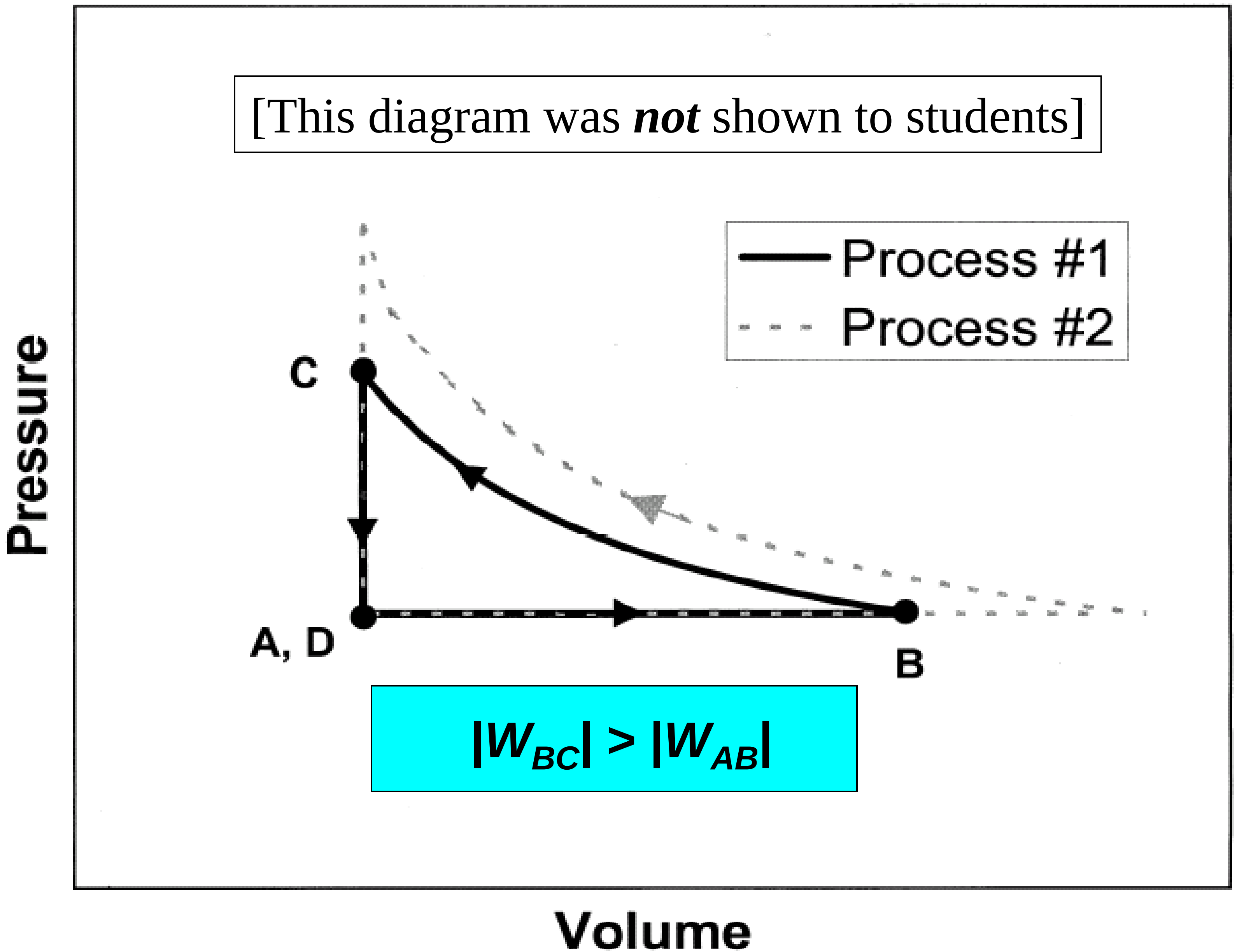
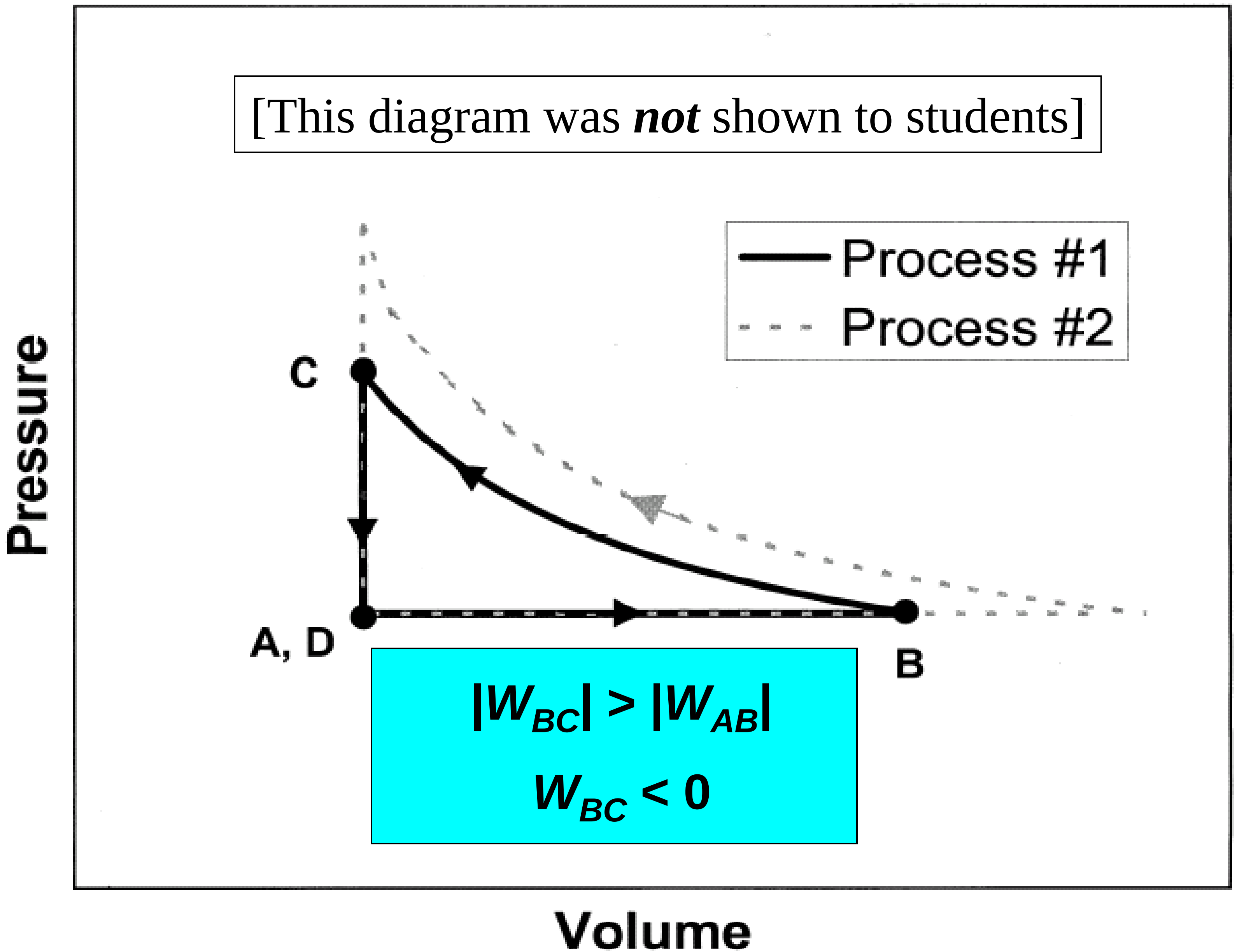
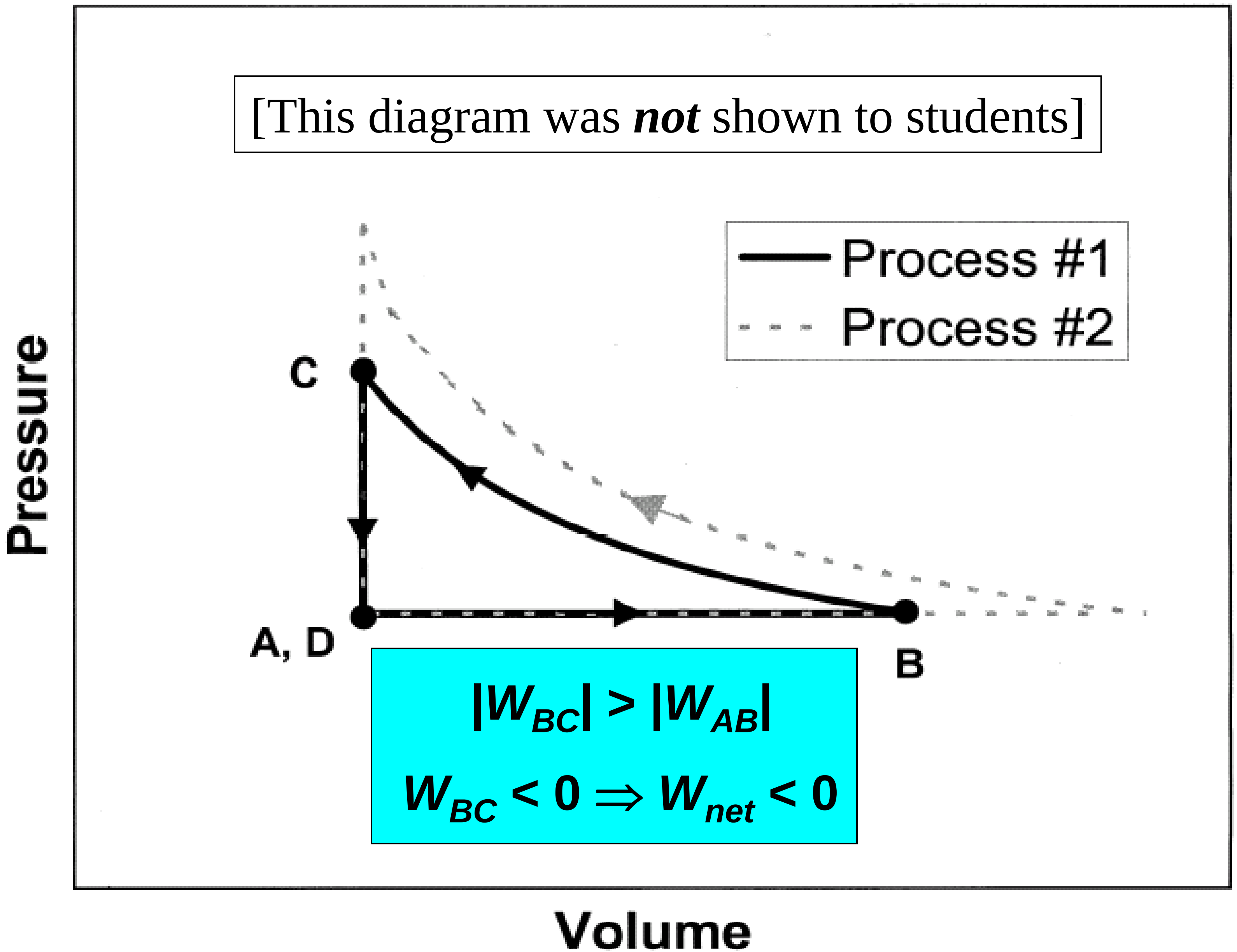
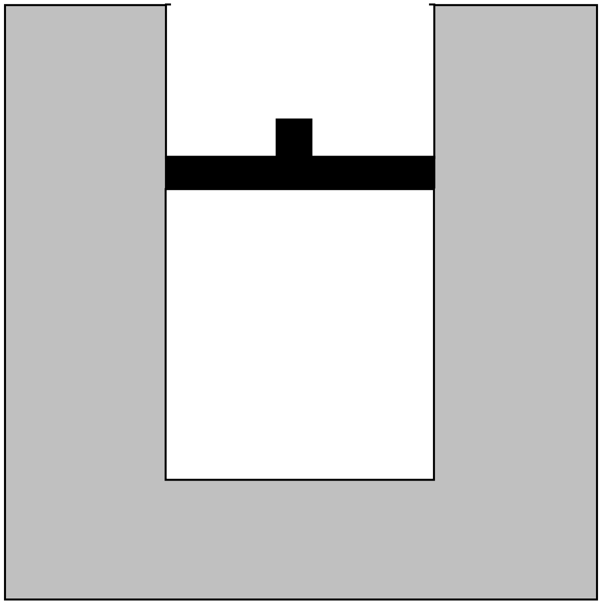
Process #1
Process #2
C
A, D
B
Pressure
Volume


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


[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
$|W_{BC}| > |W_{AB}|$
$W_{BC} < 0 \Rightarrow W_{net} < 0$
Pressure
Volume



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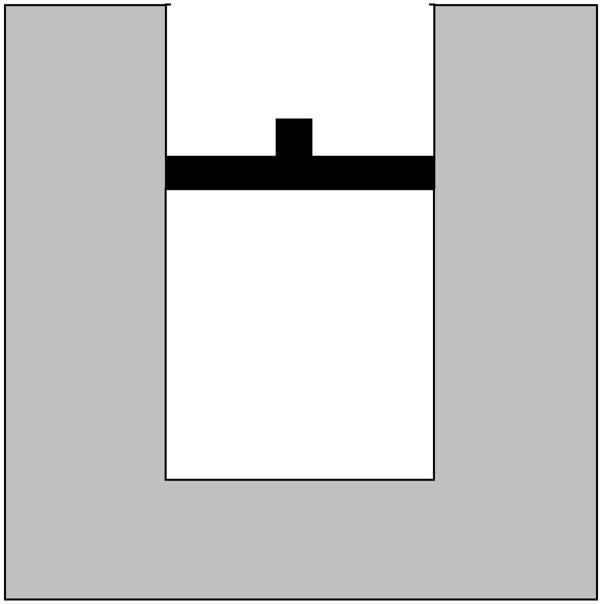

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Results on Question #6 (i)

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

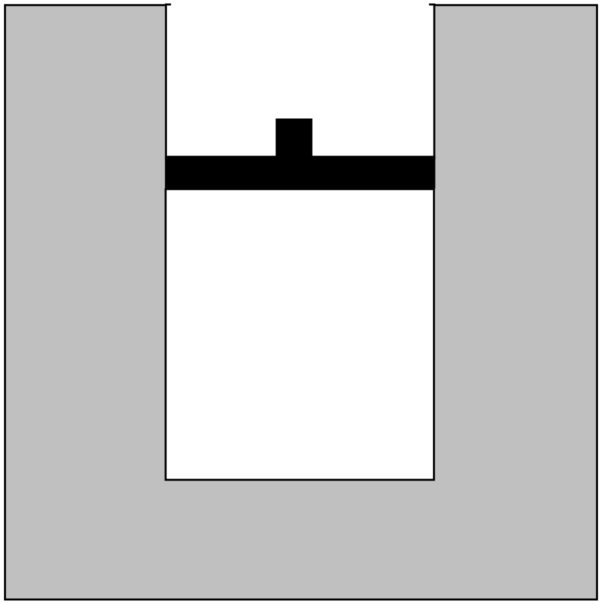
Interview sample: 19%

Upper-level students: 10%

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

Interview sample: 63%

Upper-level students: 45%



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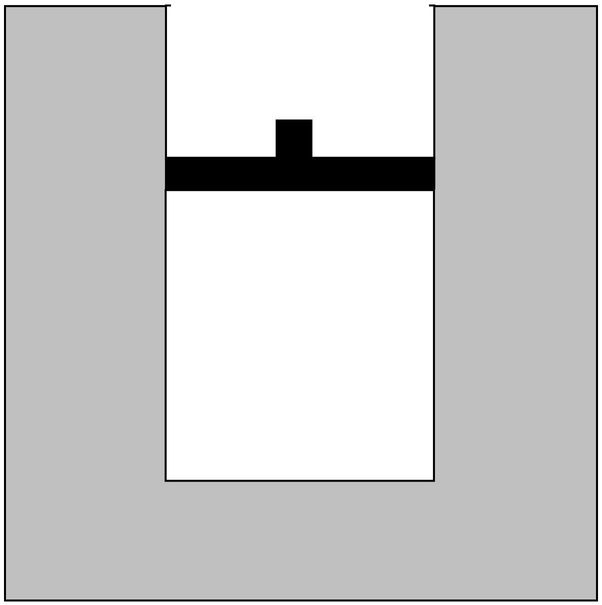

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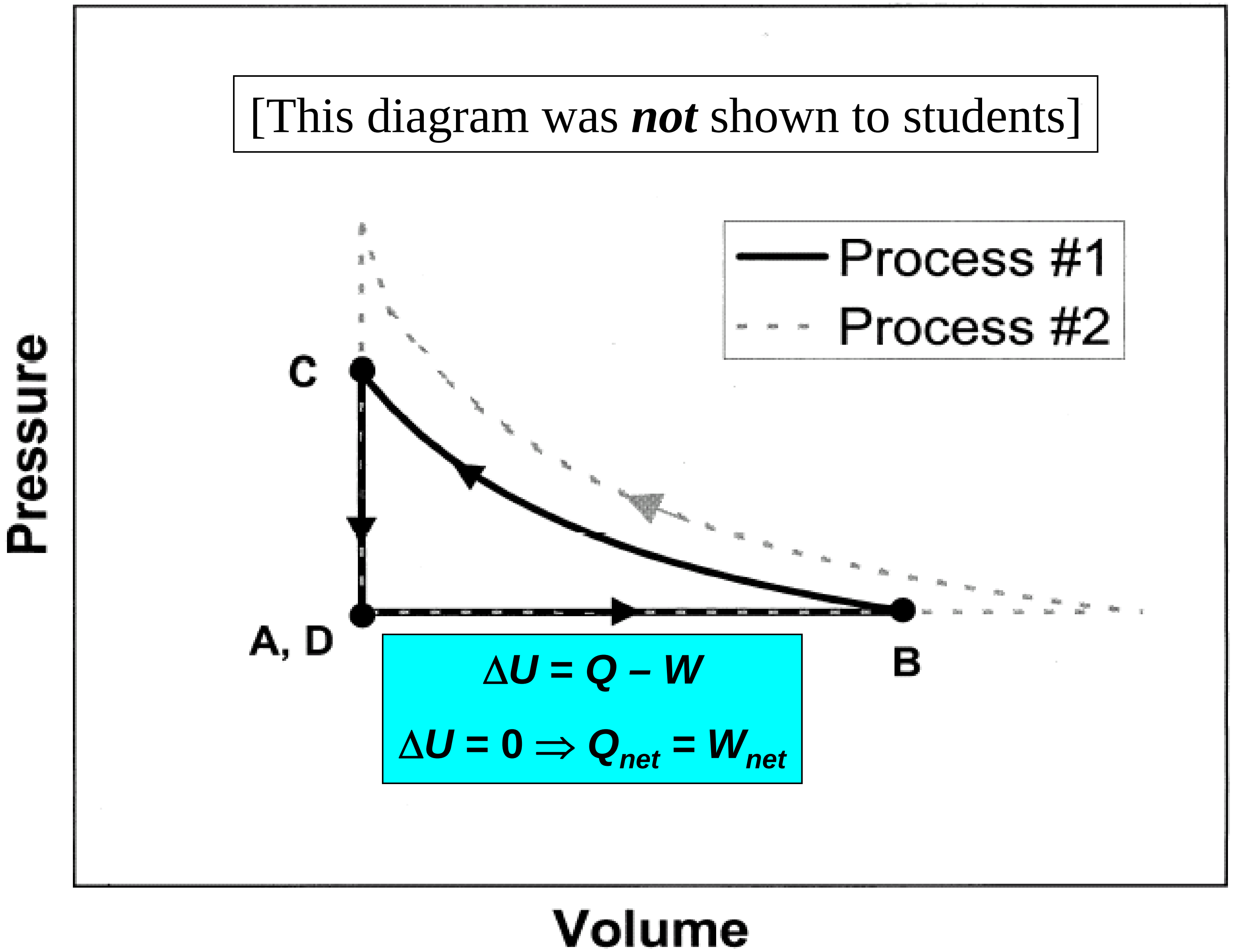
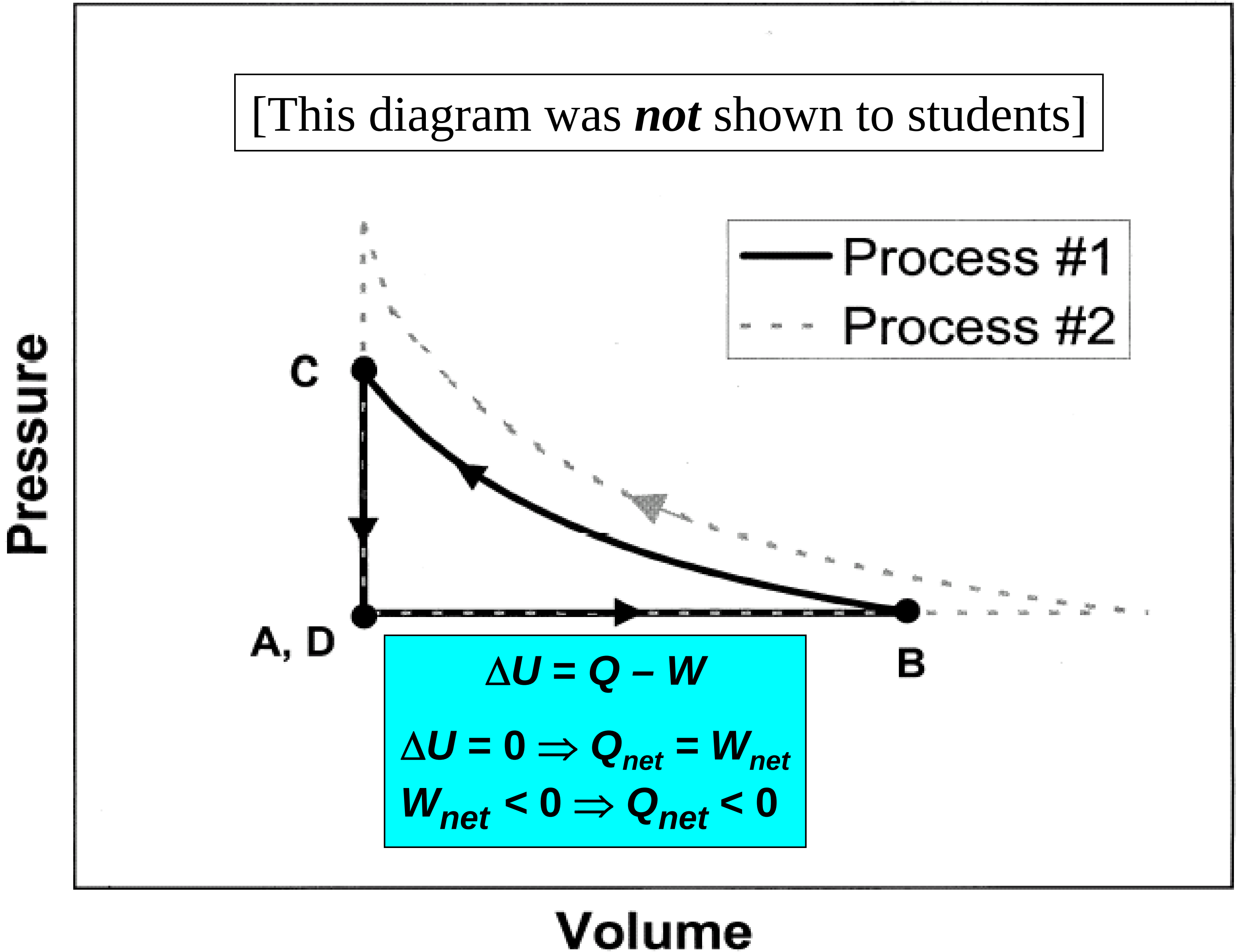

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
$\Delta U = Q - W$
$\Delta U = 0 \Rightarrow Q_{net} = W_{net}$
Pressure
Volume

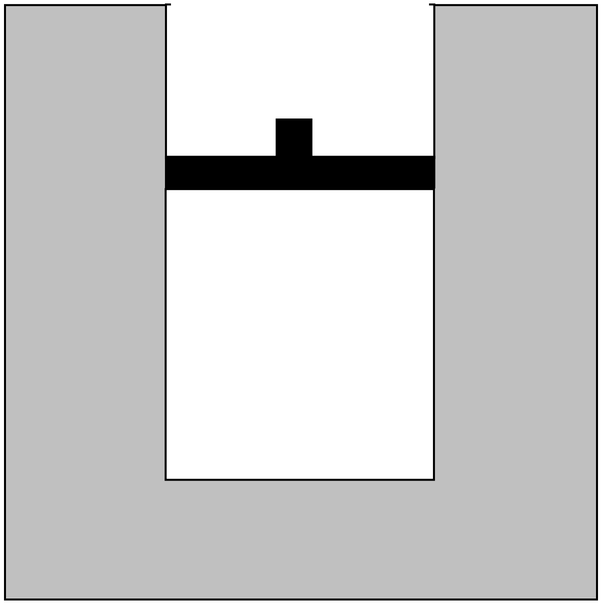
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

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

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



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?**

Results on Question #6 (ii)

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

Interview sample: 16%

Upper-level students: 20%

(b) $Q_{net} = 0$:

Interview sample: 69%

Upper-level students: 80%

Most students thought that Q_{net} and/or W_{net} must be equal to zero

- 50% of the 2004 Upper-level students initially believed that both the net work done ***and*** the total heat transferred would be zero.
- Only one out of 16 Upper-level students answered both parts of Question #6 correctly on the pre-test.

Entropy and Second-Law Questions

- Heat-engine questions
- “Spontaneous-process” question

Entropy and Second-Law Questions

- Heat-engine questions
- “Spontaneous-process” question

Spontaneous Process Question

[Introductory-Course Version]

For each of the following questions consider a system undergoing a naturally occurring ("spontaneous") process. The system can exchange energy with its surroundings.

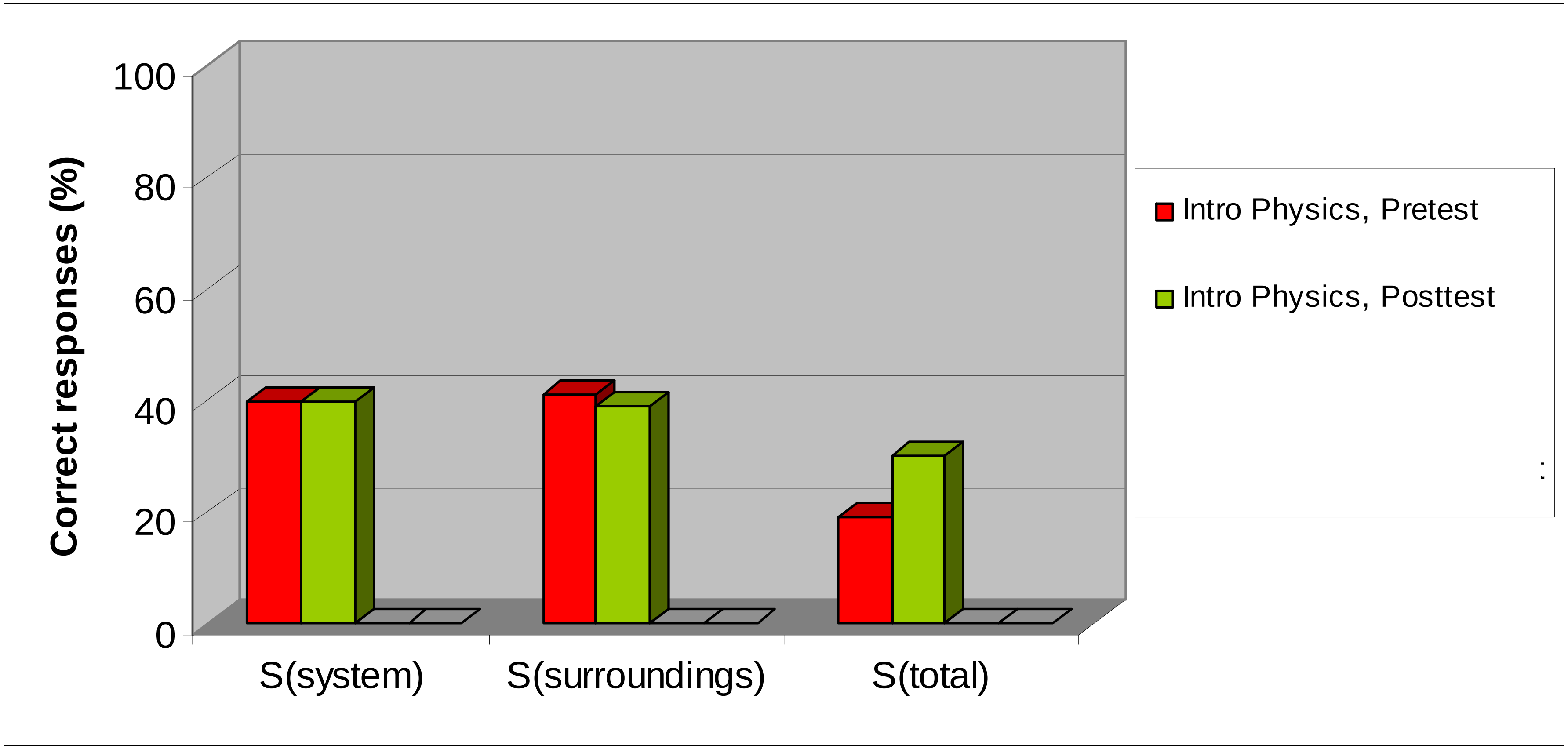
A. During this process, does the entropy of the **<u>system</u>** [S_{system}] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

B. During this process, does the entropy of the **<u>surroundings</u>** [$S_{surroundings}$] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

C. During this process, does the entropy of the system *plus* the entropy of the surroundings [$S_{system} + S_{surroundings}$] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

Responses to Spontaneous-Process Questions

Introductory Students



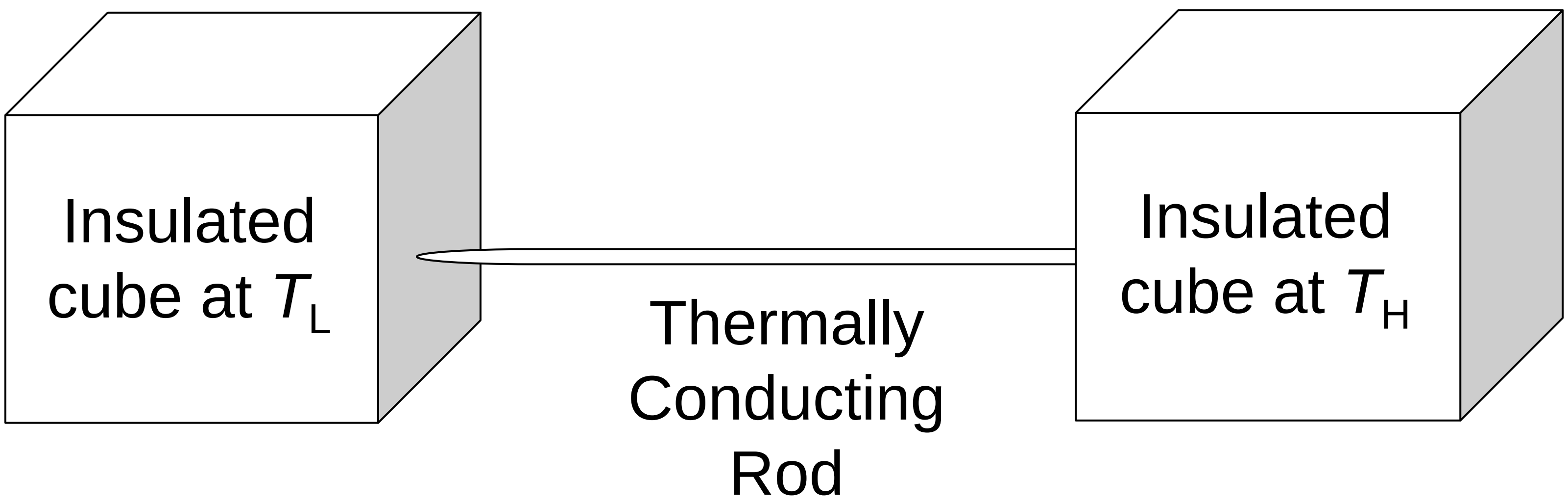
On each question, fewer than 40% answered correctly

Introductory Physics Students' Thinking on Spontaneous Processes

- Tendency to assume that "system entropy" must *always* increase
- Slow to accept the idea that entropy of system plus surroundings ***increases***
  - *Most students give incorrect answers to all three questions*

Entropy Tutorial

(draft by W. Christensen and DEM, undergoing class testing)



- Consider slow heat transfer process between two thermal reservoirs (insulated metal cubes connected by thin metal pipe)
  - Does total energy change during process?
  - Does total entropy change during process?

Entropy Tutorial

(draft by W. Christensen and DEM, undergoing class testing)

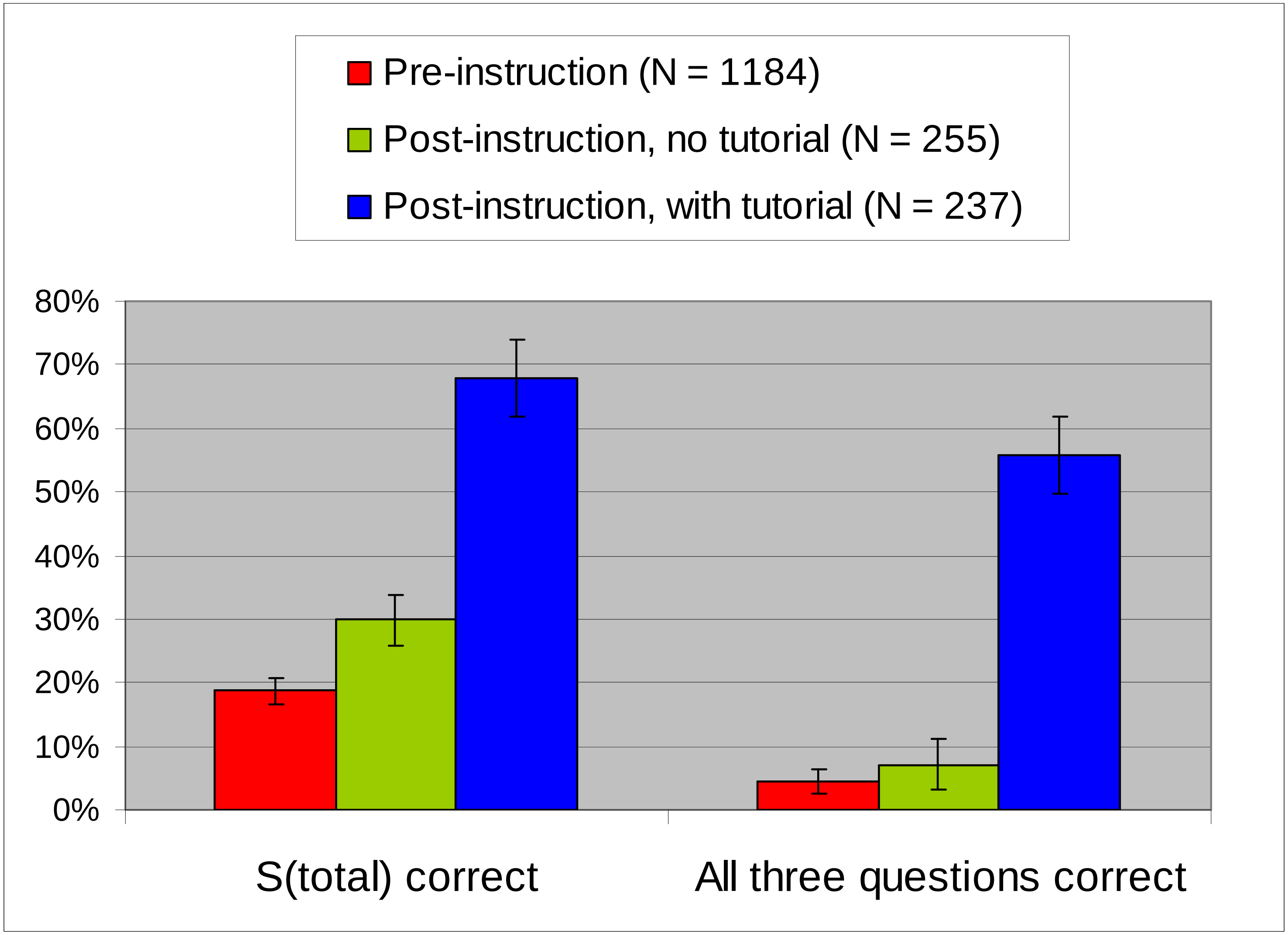
- Guide students to find that:

$$\Delta S_{total} = \frac{Q}{T_{cold\ reservoir}} - \frac{Q}{T_{hot\ reservoir}} > 0$$

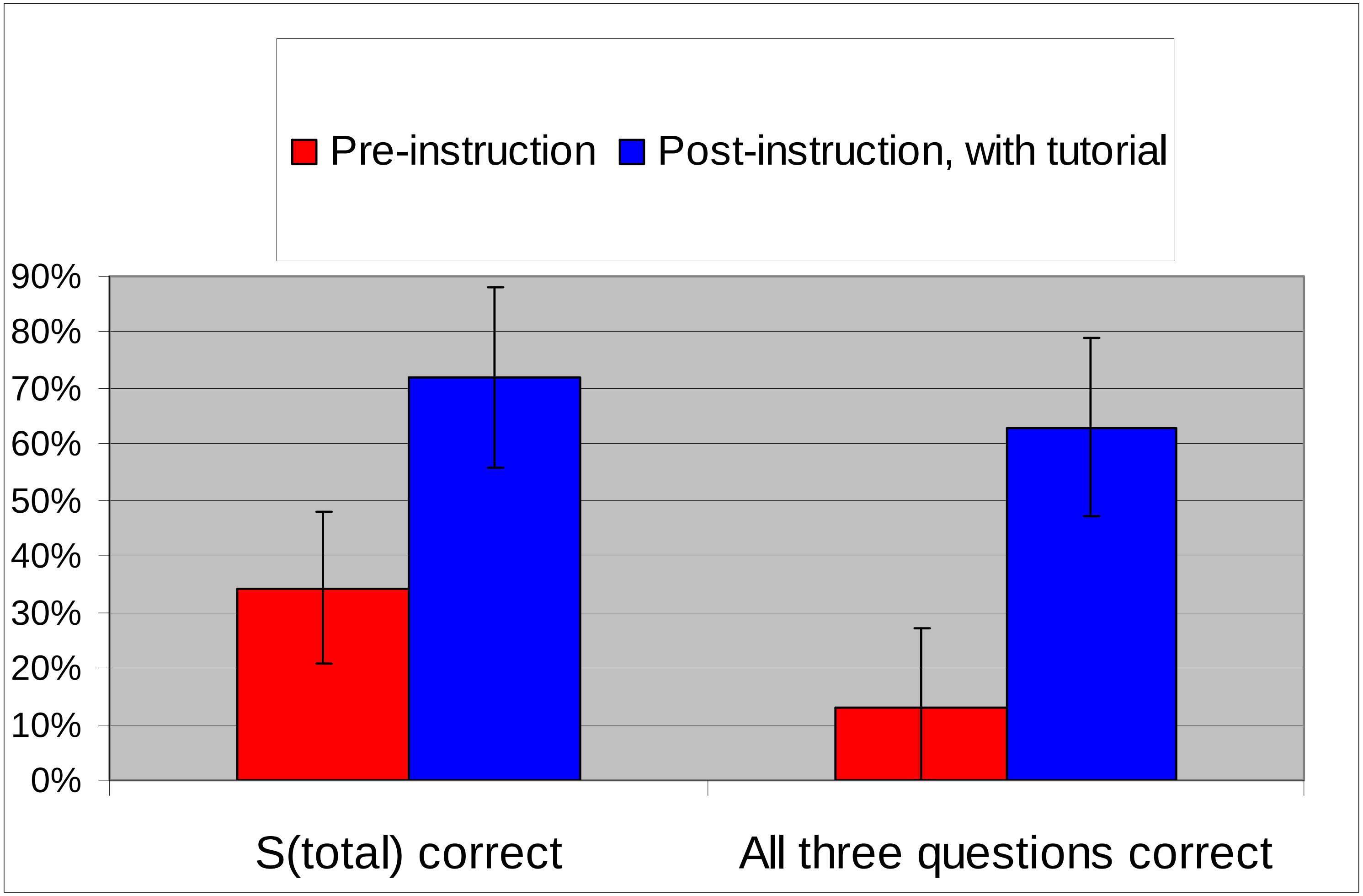
and that definitions of “system” and “surroundings” are arbitrary

Preliminary results are promising…

Responses to Spontaneous-Process Questions
Introductory Students



Responses to Spontaneous-Process Questions
Intermediate Students (*N* = 32, Matched)



Summary

- Most students completing introductory physics courses retain significant difficulties with fundamental thermodynamic concepts.
- Conceptual difficulties persist for many students beginning upper-level thermal physics course.
- Research-based curricular materials yield promising outcomes in preliminary testing.