Improving Instruction in Thermal Physics through Research on Students' Thinking

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Collaborators

- Tom Greenbowe (Iowa State University; Chemistry)
- John Thompson (U. Maine; Physics)
- Michael Loverude (California State U., Fullerton; Physics)
- Warren Christensen (North Dakota State U.; Physics)

Students

- Ngoc-Loan Nguyen (ISU M.S. 2003)
- Tom Stroman (ISU graduate student)

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- NSF Division of Physics

Outline

1. Overview of findings in the literature
2. Overview of our investigations
3. Detailed findings: First-law topics, introductory vs. advanced students
4. Detailed findings: Second-law topics
5. Some pedagogical strategies

Background

- Research on learning of thermal physics in introductory courses in USA:
  - algebra-based introductory physics
    Loverude, Kautz, and Heron, *Am. J. Phys*. **70**, 137 (2002)
  - sophomore-level thermal physics
    Loverude, Kautz, and Heron, *Am. J. Phys*. **70**, 137 (2002); Cochran and Heron, Am. J. Phys. **74**, 734 (2006)
  - calculus-based introductory physics
    DEM, *Am. J. Phys*. **72**, 1432 (2004); Christensen, Meltzer, and Ogilvie, *Am. J. Phys*. **77**, 907 (2009); also some data from LKH, 2002
- Focus of current work:
  - research and curriculum development for upper-level (junior-senior) thermal physics course

Student Learning of Thermodynamics

Studies of university students have revealed learning difficulties with concepts related to the first and second laws of thermodynamics:

USA

M. E. Loverude, C. H. Kautz, and P. R. L. Heron (2002);
D. E. Meltzer (2004);
M. Cochran and P. R. L. Heron (2006)
Christensen, Meltzer, and Ogilvie (2009).

Finland

Leinonen, Räsänen, Asikainen, and Hirvonen (2009)

Germany

R. Berger and H. Wiesner (1997)

France

S. Rozier and L. Viennot (1991)

UK

J. W. Warren (1972)

A Summary of Some Key Findings…

- *"Target Concepts":* Instructors' objectives for student learning
- *"Students (tend to) believe…" [etc.]:* Statements about thinking characteristic of significant fraction of students

Target Concept 1: A *state* is characterized by well-defined values for energy and other variables.

- Students seem comfortable with this idea within the context of energy, temperature, and volume, but *not* entropy.[2,3,4]
- Students overgeneralize the state function concept, applying it inappropriately to heat and work.[1,2]
- ***Summary:*** Students are inconsistent in their application of the state-function concept.

[1]Loverude et al., 2002
[2]Meltzer, 2004
[3]Meltzer, 2005 [PER Conf. 2004]
[4]Bucy, et al., 2006 [PER Conf. 2005]

Target Concept 2: System *loses* energy through expansion work, but *gains* energy through compression work.

- Many students believe either that “no work” or *positive* work is done on the system[1,2] during an expansion, rather than negative work.
- Students fail to recognize that system loses energy through work done in an expansion,[2] or that system gains energy through work done in a compression.[1]
- ***Summary:*** Students fail to recognize the energy transfer role of work in thermal context.

[1]Loverude et al., 2002
[2]Meltzer, 2004

Target Concept 3: Temperature is proportional to average kinetic energy of molecules, and inter-molecular collisions can't increase temperature.

- Many students believe that molecular kinetic energy can increase during an isothermal process.[2]
- Students believe that intermolecular collisions lead to net increases in kinetic energy and/or temperature.[1,2,3,4]
- ***Summary:*** Students overgeneralize energy *transfer* role of molecular collisions so as to acquire a belief in energy *production* role of such collisions.

[1]Loverude et al., 2002
[2]Meltzer, 2004
[3]Rozier and Viennot, 1991
[4]Leinonen et al., 2009

Target Concept 4: Isothermal processes involve exchanges of energy with a thermal "reservoir."

- Students do not recognize that energy transfers must occur (through heating) in a quasistatic isothermal process.[2,4]
- Students do not recognize that a thermal reservoir does not undergo temperature change even when acquiring energy.[2]
- ***Summary:*** Students fail to recognize idealizations involved in definitions of "reservoir" and "isothermal process."

[2]Meltzer, 2004 [4]Leinonen et al., 2009

Target Concept 5: Both heat transfer and work are process-dependent quantities, whose net values in an arbitrary cyclic process are non-zero.

- Students believe that heat transfers and work done in different processes linking common initial and final states must be equal.[1,2]
- Students believe that that net heat transfer in a cyclic process must be zero since $\Delta T = 0$, and that net work done must be zero since $\Delta V = 0$.[1,2]
- ***Summary:*** Students fail to recognize that neither heat nor work is a state function.

[1]Loverude et al., 2002
[2]Meltzer, 2004

Research on Student Learning in Thermal Physics

- Investigate student learning of both macroscopic and microscopic thermodynamics
- Probe evolution of students' thinking from introductory through advanced-level course
- Develop research-based curricular materials to improve instruction

Phase I:
Student Learning of Thermodynamics in Introductory Physics

- Investigation of first-year, second-semester calculus-based physics course (mostly engineering students) at Iowa State University.
- Written diagnostic questions administered last week of class in 1999, 2000, and 2001 (N_{total} = 653).
- Detailed interviews (avg. duration $\geq$ one hour) carried out with 32 volunteers during 2002 (total class enrollment: 424).
  - *interviews carried out after all thermodynamics instruction completed*

Phase II:

Student Learning in Upper-Level Thermal Physics

- Investigation of students in third-year course on classical and statistical thermodynamics

- **Students enrolled** [$N_{initial}$ = 14 (*2003*) and 19 (*2004*)]
  - ≈ 90% were physics majors or physics/engineering double majors
  - all had studied thermodynamics (some at advanced level)

Course taught by DEM using lecture + interactive-engagement

Performance Comparison: Upper-level vs. Introductory Students

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

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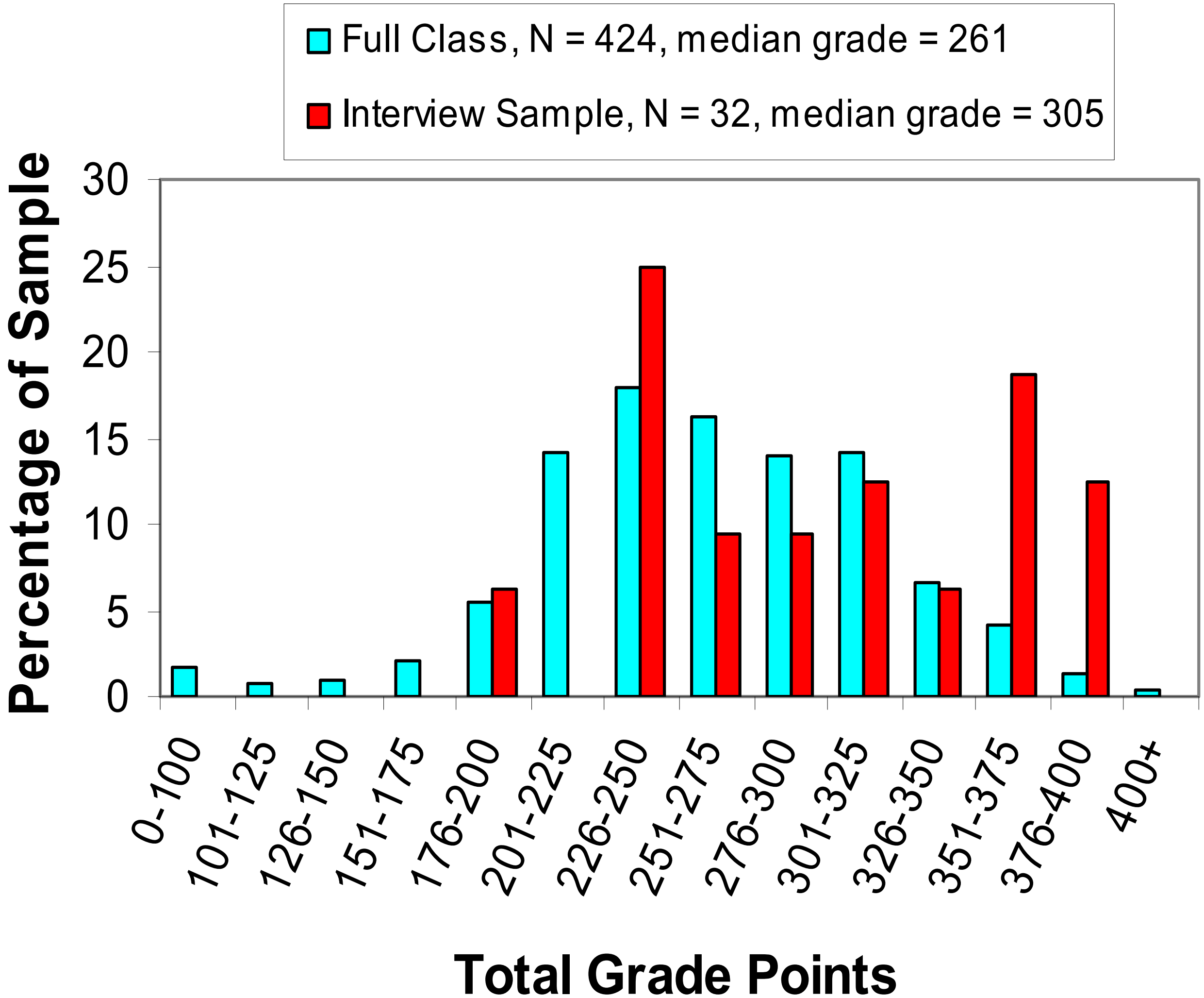
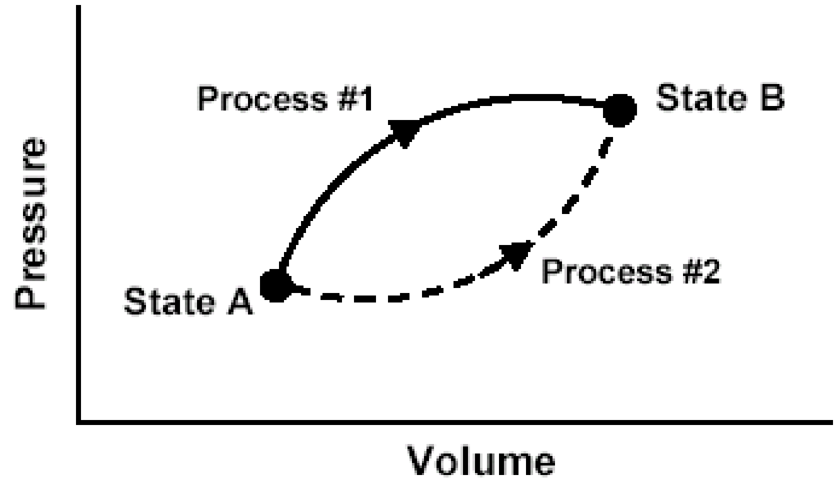
Grade Distributions: Interview Sample vs. Full Class



***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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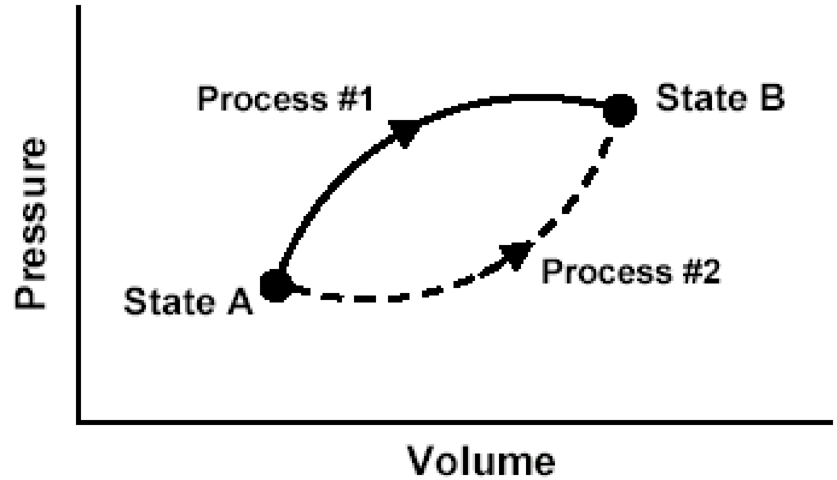

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1. Is *W* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2? Explain.

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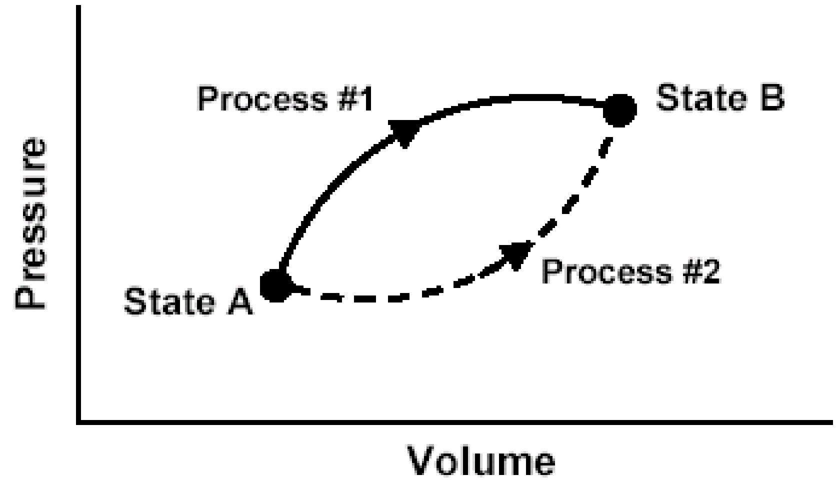

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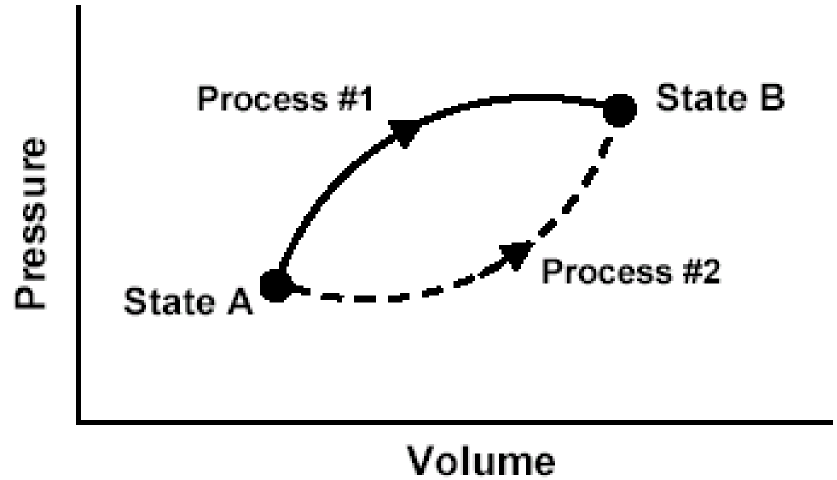

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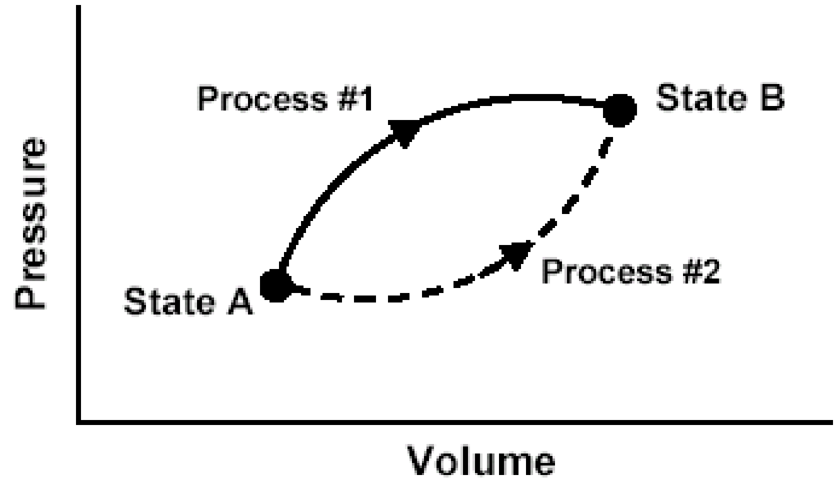

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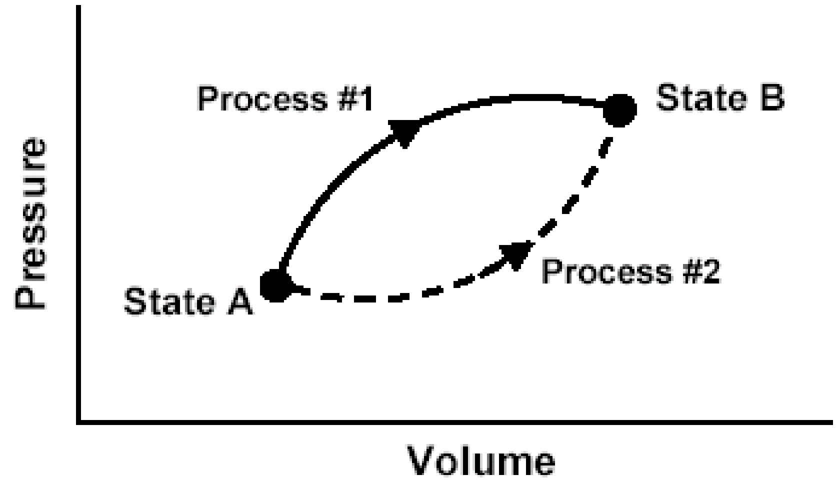

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Responses to Diagnostic Question #1
(Work question)

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	**2002** Introductory Physics (Post-test) Interview Sample (*N*=32)	**2004** Thermal Physics (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
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	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
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$W_1 = W_2$	**30%**	**22%**	**20%**

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About one-fifth of Thermal Physics students believe work done is equal in both processes

Explanations Given by Thermal Physics 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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➡ **Some students come to associate work with phrases only used in connection with state functions.**

Confusion with mechanical work done by conservative forces?

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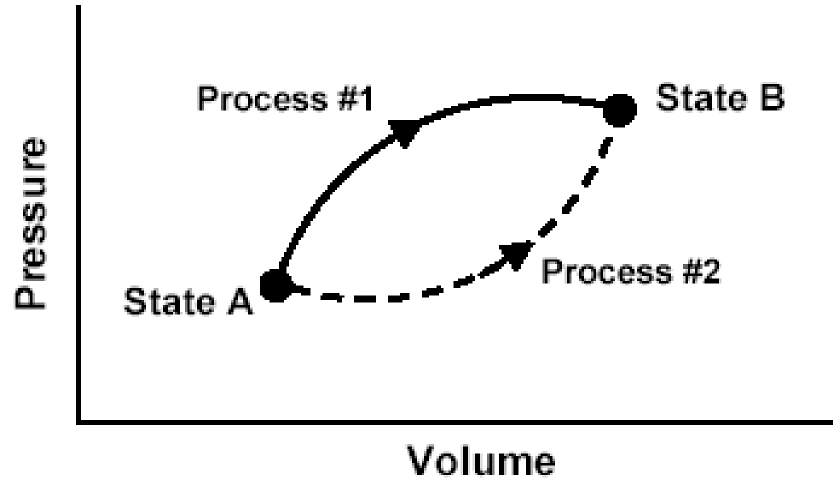

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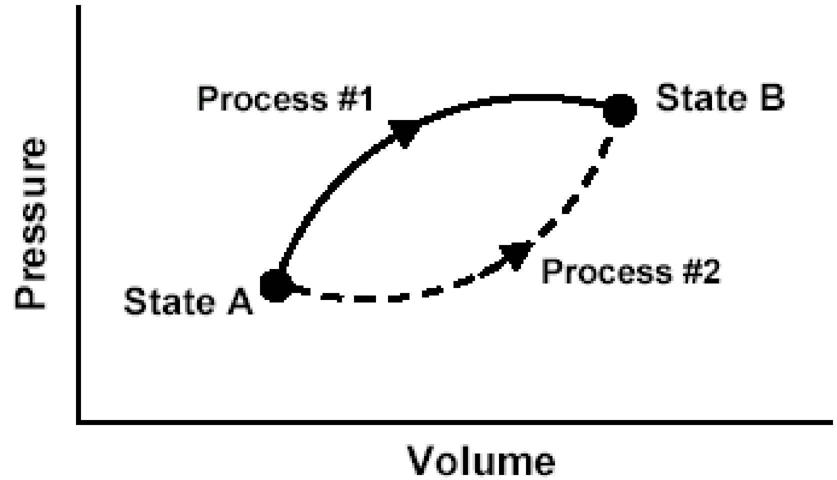

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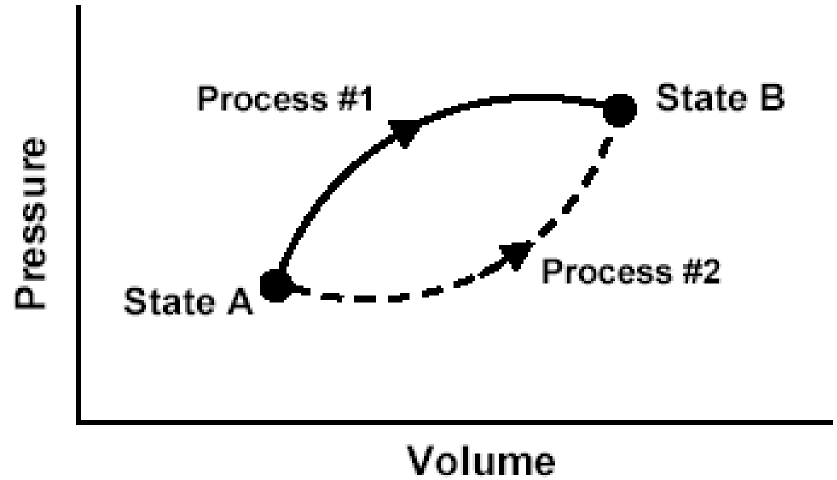
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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



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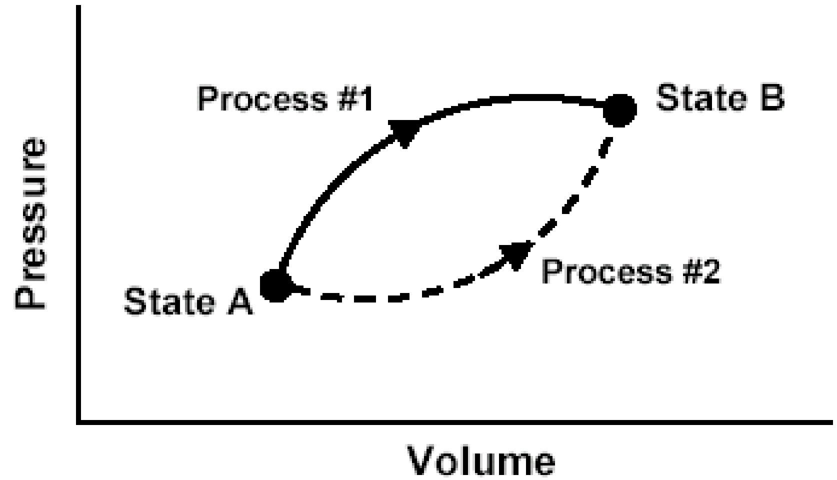
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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** Thermal Physics (Pretest) (N=19)
$Q_1 > Q_2$			
$Q_1 = Q_2$			
$Q_1 < Q_2$			

Responses to Diagnostic Question #2
(Heat question)

$Q_1 = Q_2$			

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 Thermal Physics (Pretest) (*N*=33)
$Q_1 = Q_2$	38%	47%	30%

Explanations Given by Thermal Physics 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 Thermal Physics students stated or implied that heat transfer is independent of process, similar to claims made by introductory students.**

Confusion due to use of $Q = mc\Delta T$ in calorimetry problems?

Responses to Diagnostic Question #2
(Heat question)

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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** Thermal Physics (Pretest) (N=14)
$Q_1 > Q_2$	**45%**	**34%**	**35%**

Responses to Diagnostic Question #2
(Heat question)

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$Q_1 > Q_2$	**45%**	**34%**	**35%**
Correct or partially correct explanation	**11%**	**19%**	**30%**

Responses to Diagnostic Question #2
(Heat question)

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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.

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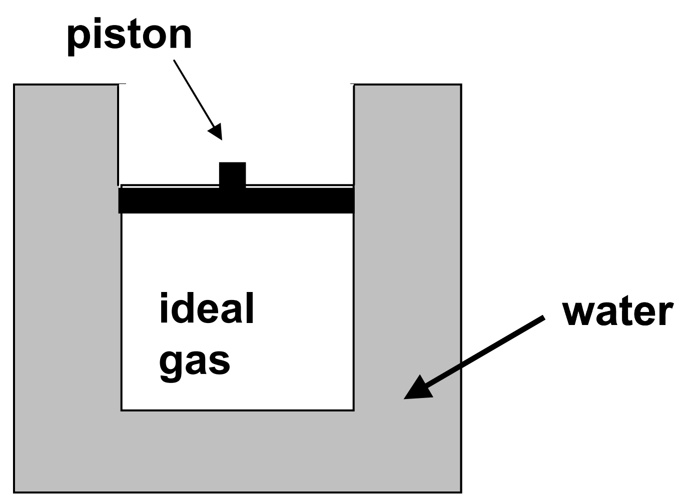
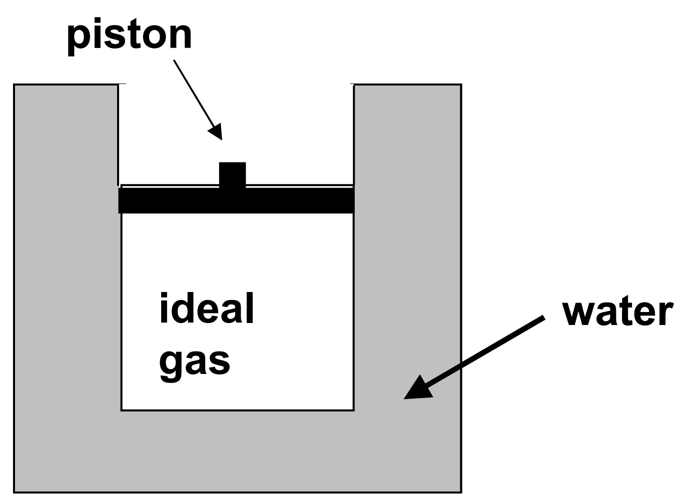


Cyclic Process Questions

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

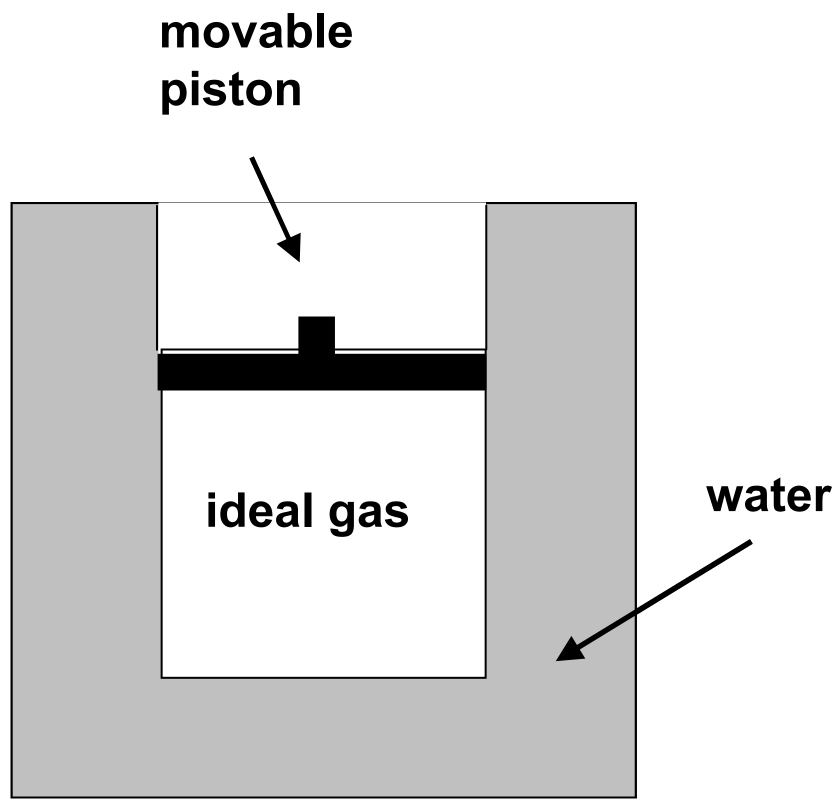
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe Process #1.

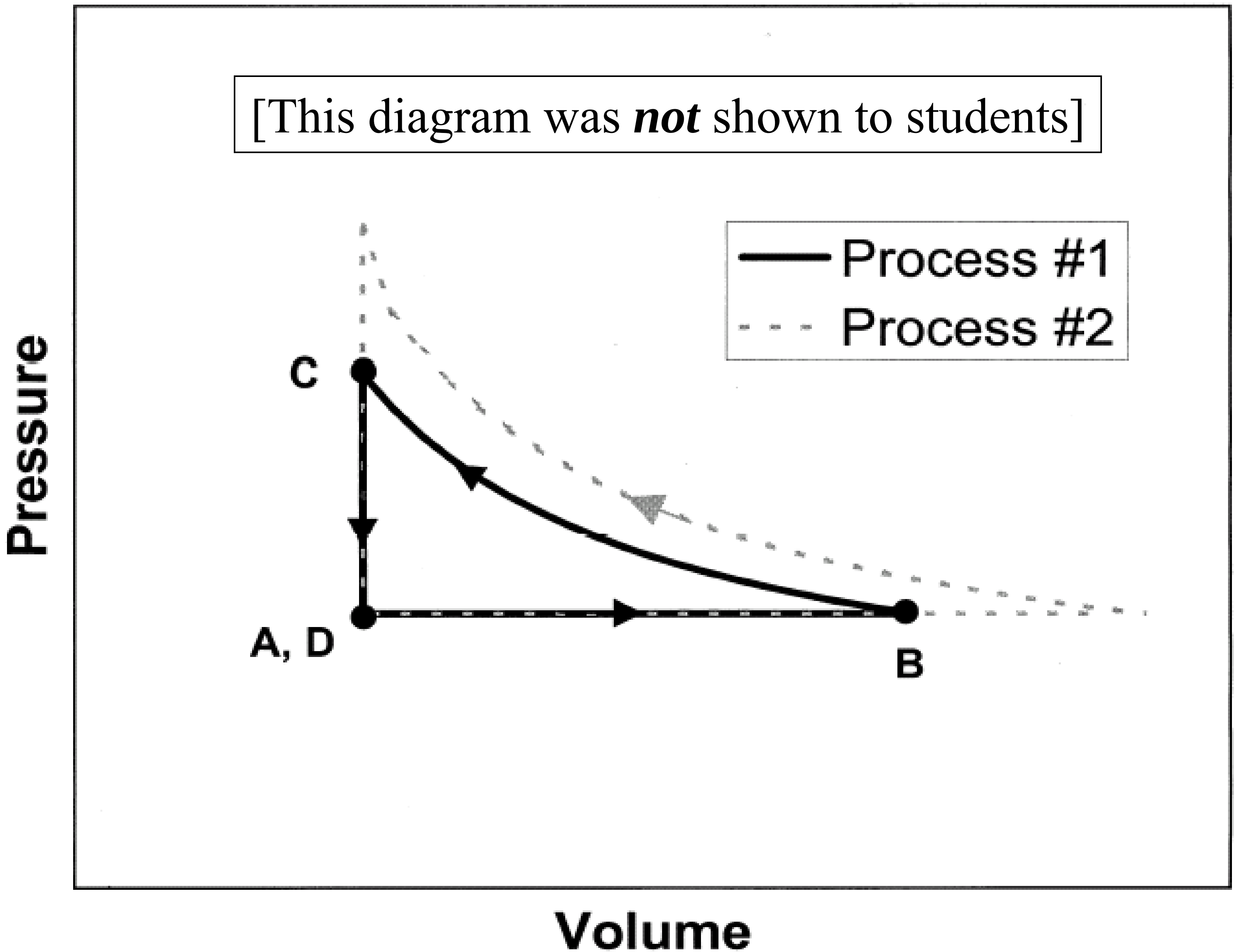


At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature

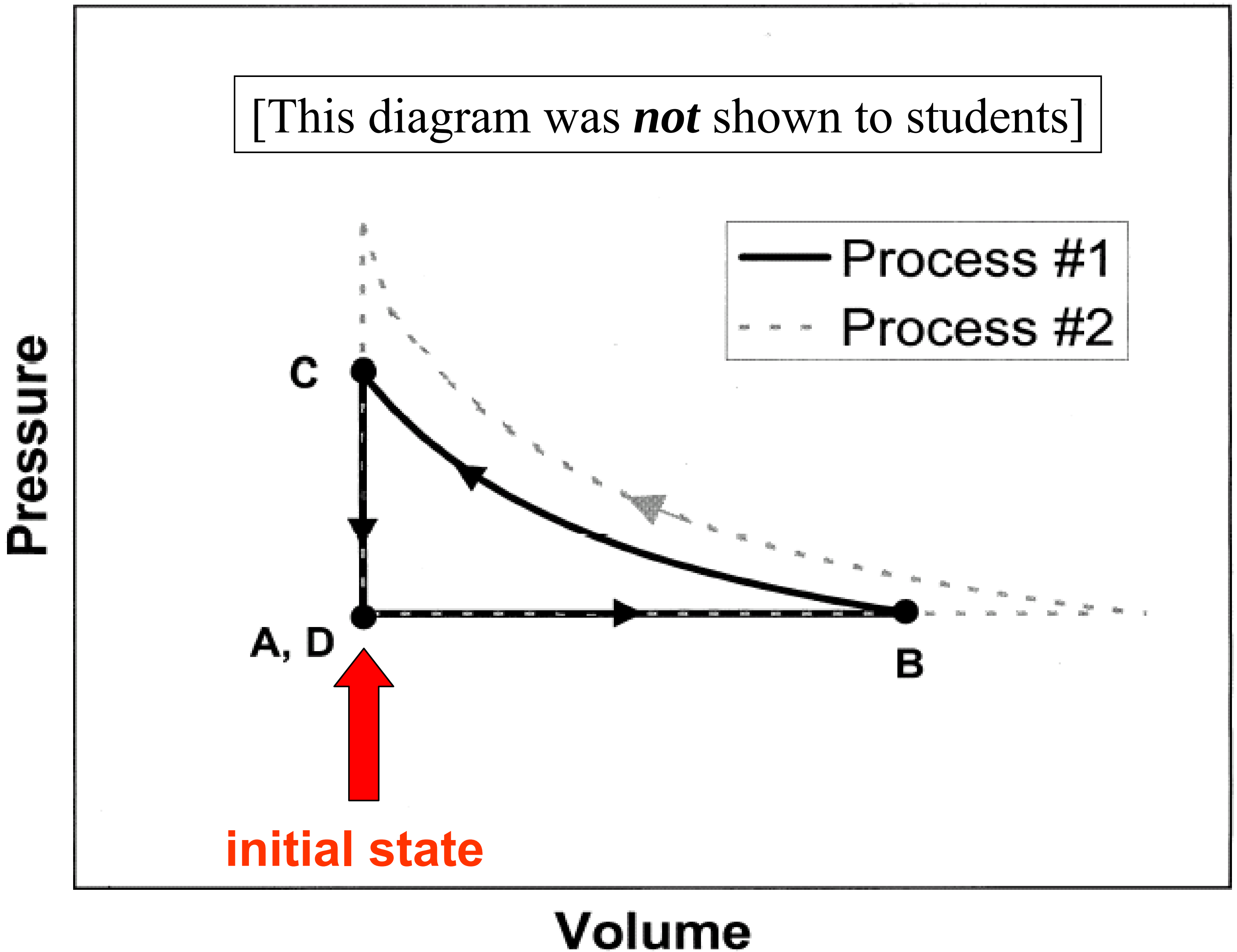
Time *A*

Entire system at room temperature.



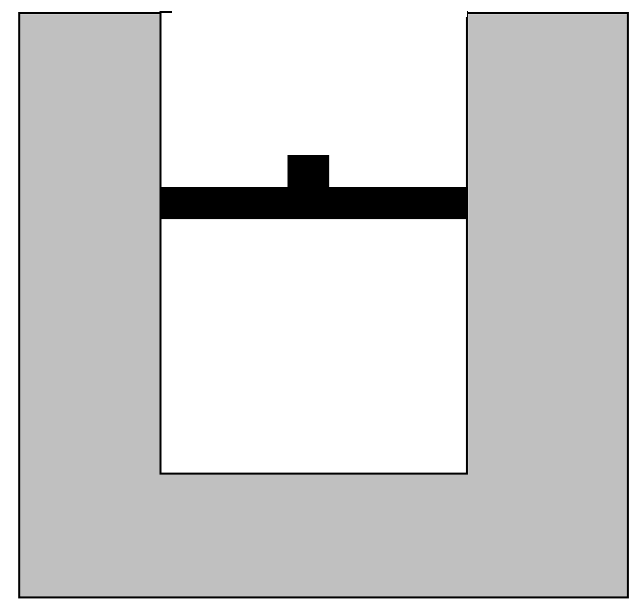


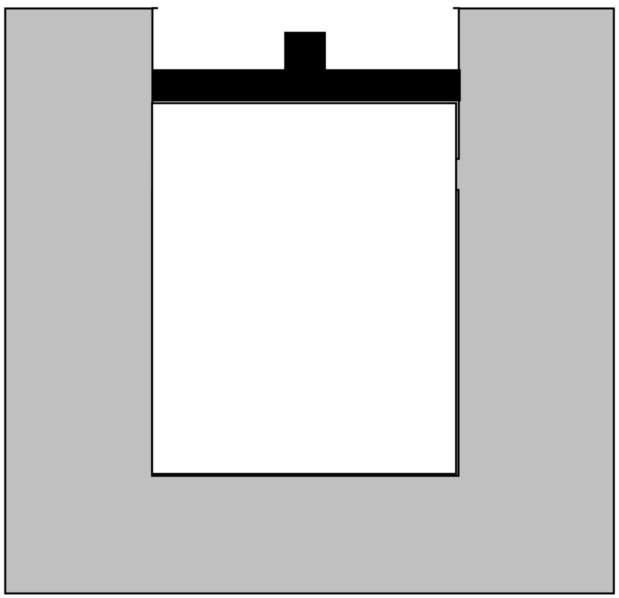
[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



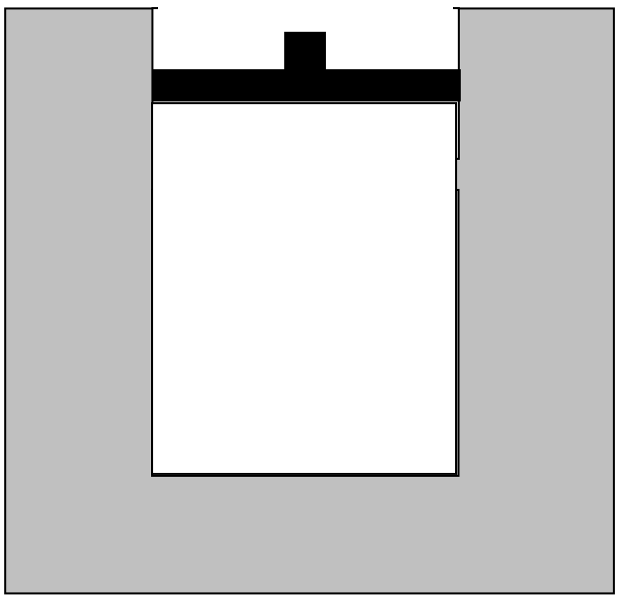
[This diagram was *not* shown to students]
Process #1
Process #2
Pressure
C
A, D
B
initial state
Volume

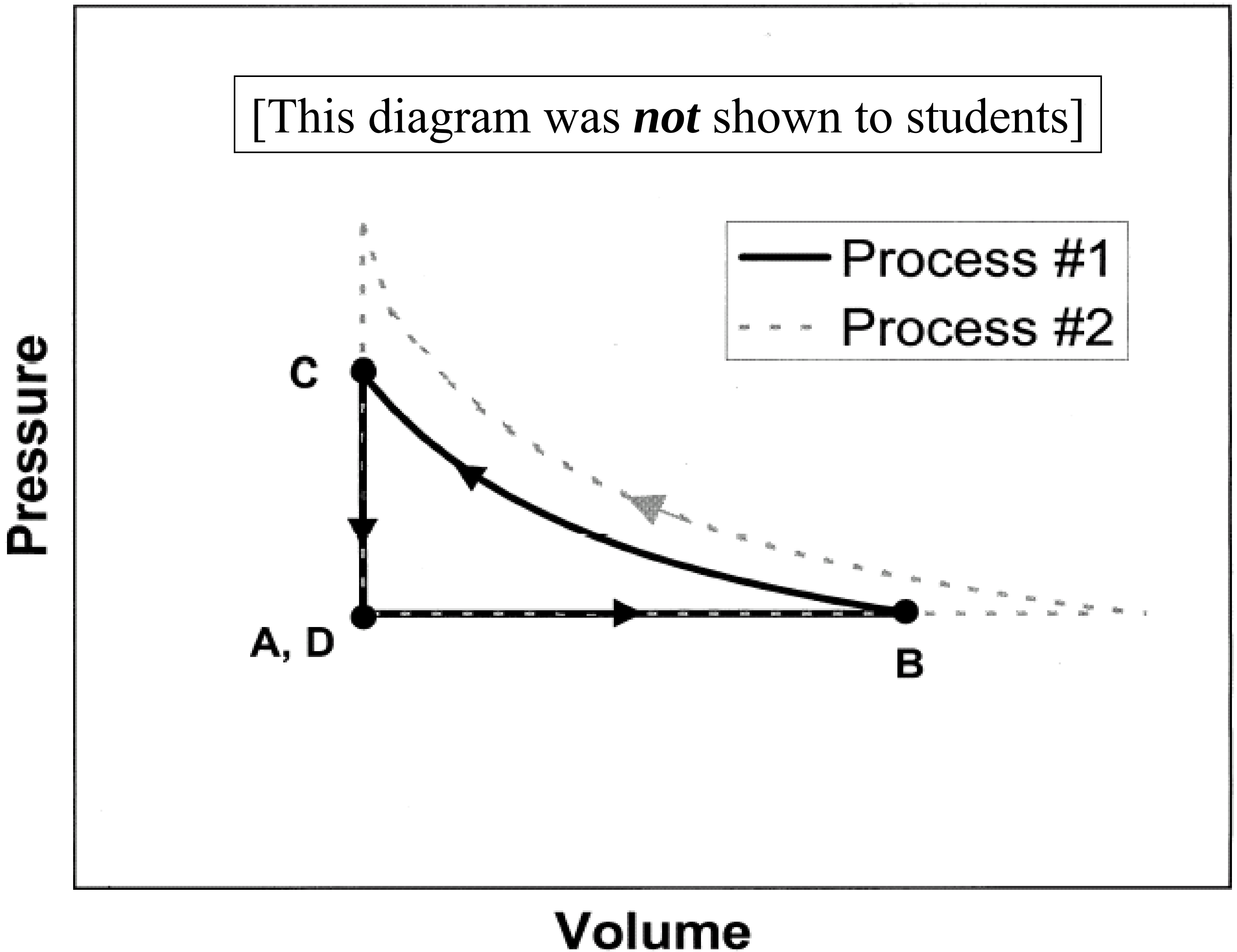
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.





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

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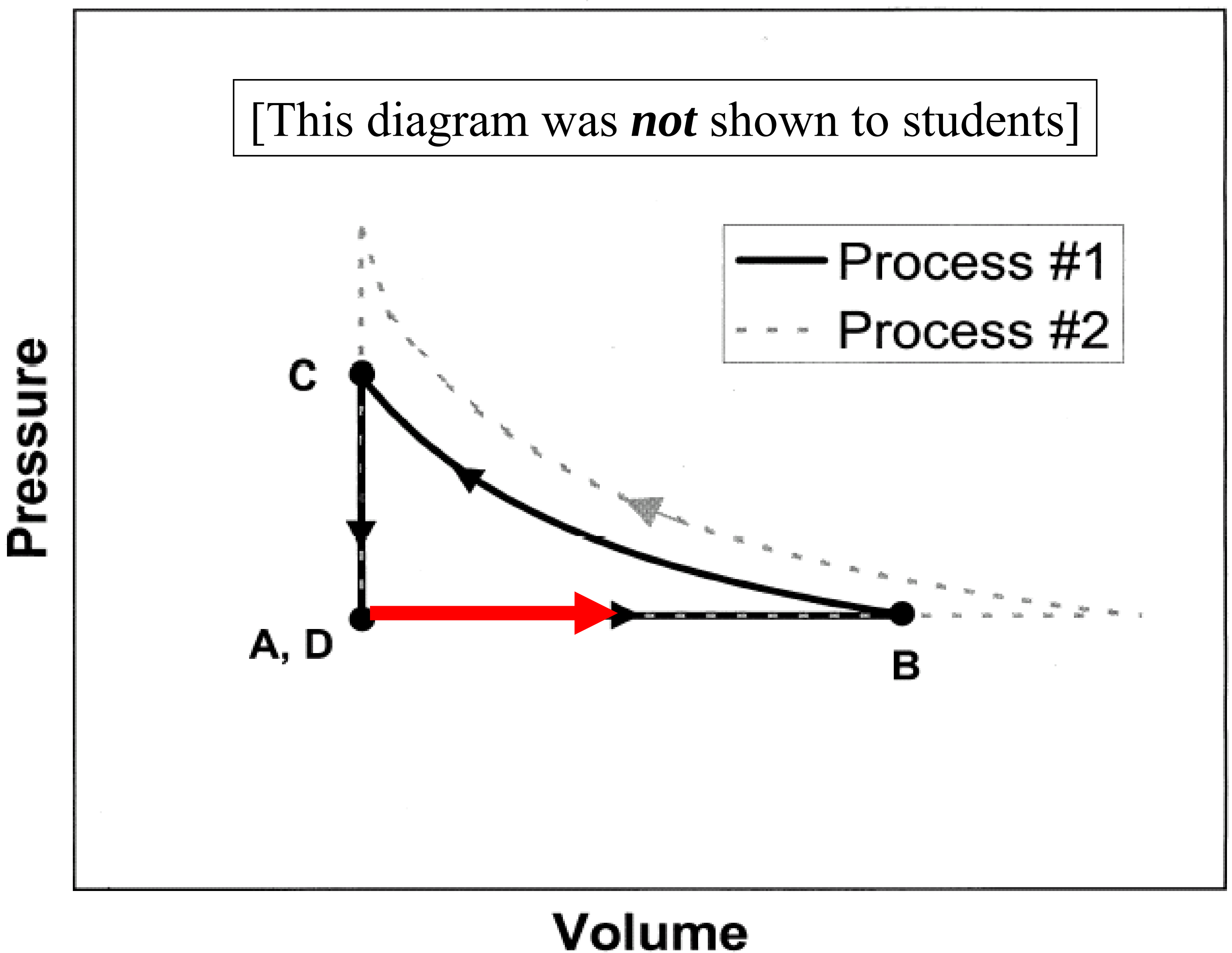
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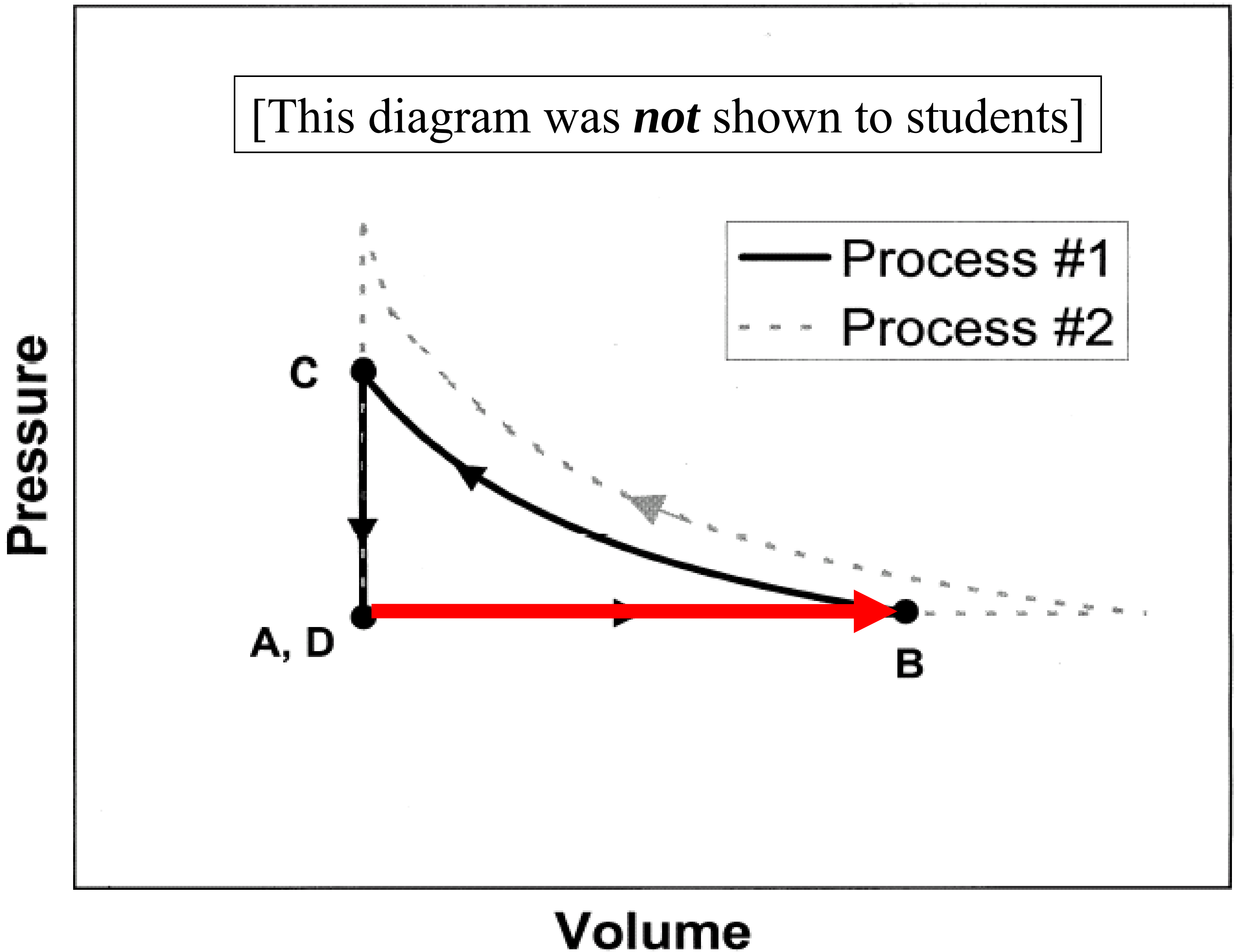
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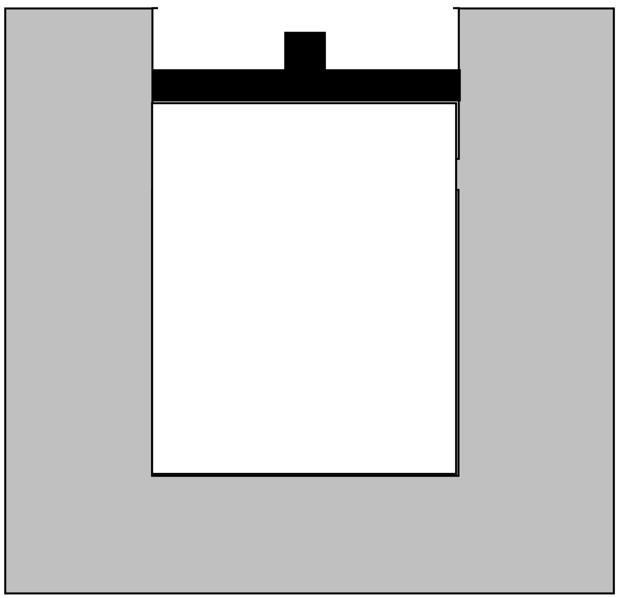
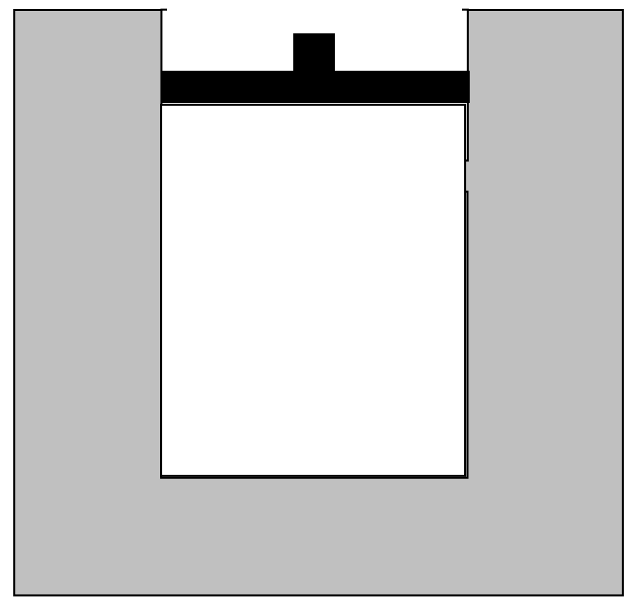
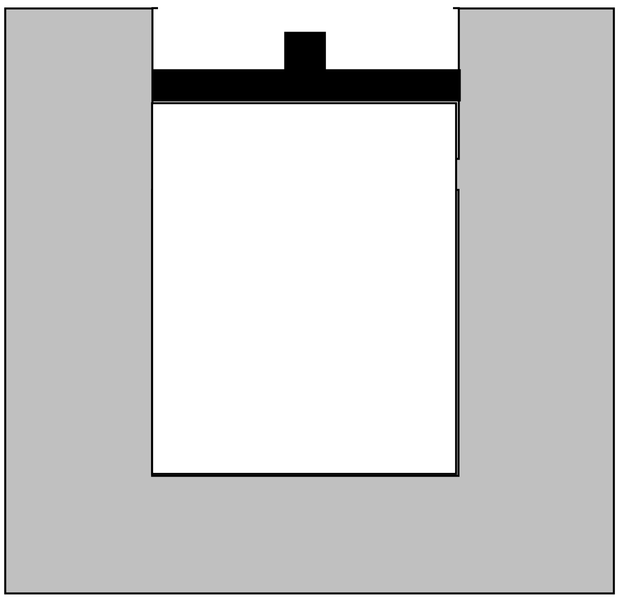
A, D
B
Pressure
Volume





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.



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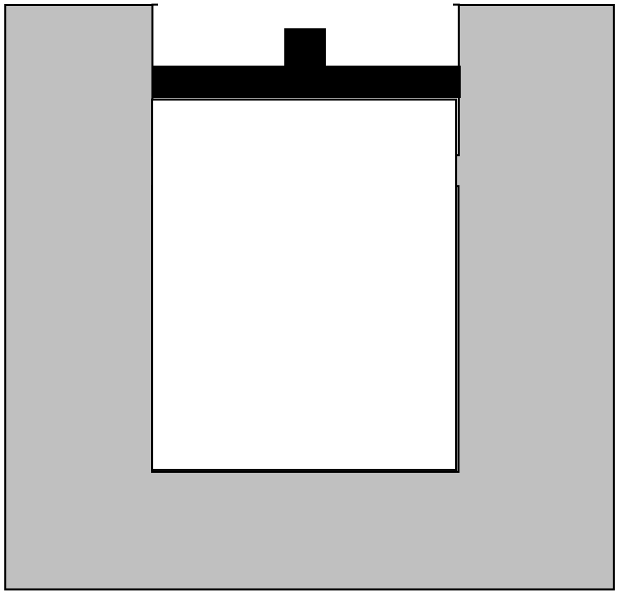

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Results on Question #1

Results on Question #1

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

Results on Question #1

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

Interview Sample: 69%; *Thermal Physics students:* 62%

Results on Question #1

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

(b) positive work done *by* gas *on* environment *[correct]:*
Interview Sample: 69%; *Thermal Physics students:* 62%

Results on Question #1

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

Interview Sample: 31%; *Thermal Physics students:* 38%

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

Interview Sample: 69%; *Thermal Physics students:* 62%

Results on Question #1

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

Interview Sample: 31%; *Thermal Physics students:* 38%

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

Interview Sample: 69%; *Thermal Physics students:* 62%

Sample explanations for (a) answer:

Results on Question #1

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Interview Sample: 31%; *Thermal Physics students:* 38%

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Interview Sample: 69%; *Thermal Physics students:* 62%

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."

Results on Question #1

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Interview Sample: 31%; *Thermal Physics students:* 38%

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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."

Results on Question #1

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

Interview Sample: 31%; *Thermal Physics students:* 38%

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Interview Sample: 69%; *Thermal Physics students:* 62%

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 believed that environment does positive work **on** *gas by* **heating***.*

Results on Question #1

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

Interview Sample: 31%; *Thermal Physics students:* 38%

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

Interview Sample: 69%; *Thermal Physics students:* 62%

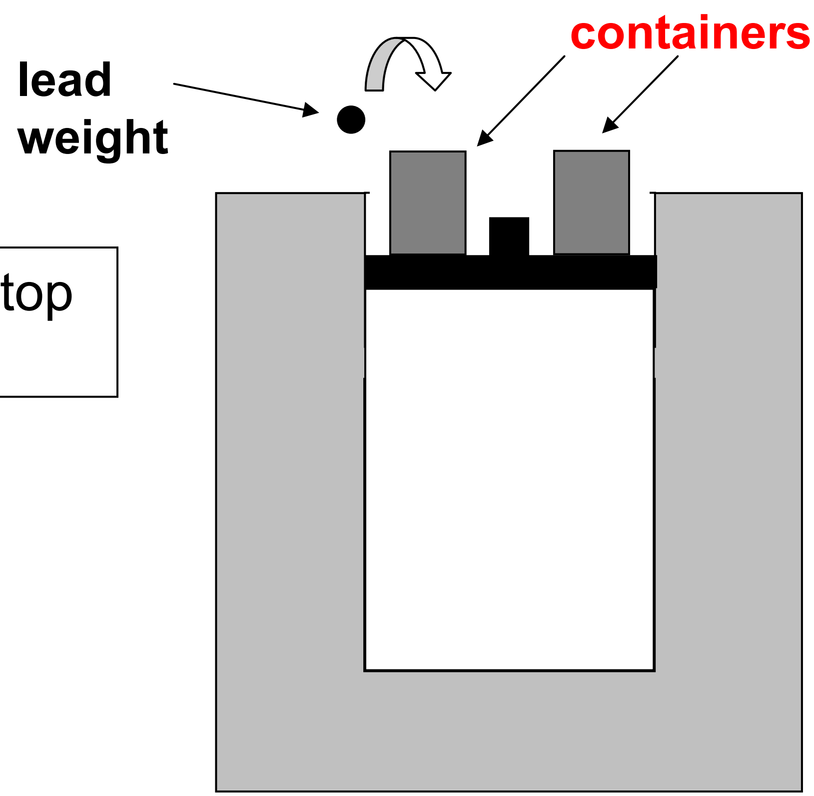
Sample explanations for (a) answer:

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

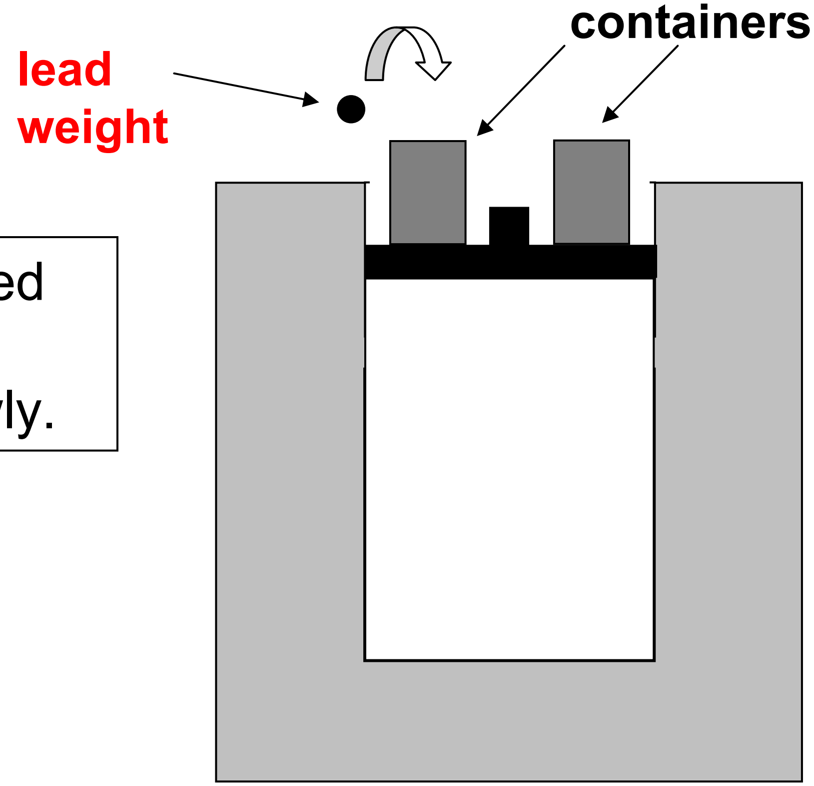
"The environment did work on the gas, since it made the gas expand and the piston moved up . . . water was heating up, doing work on the gas, making it expand."

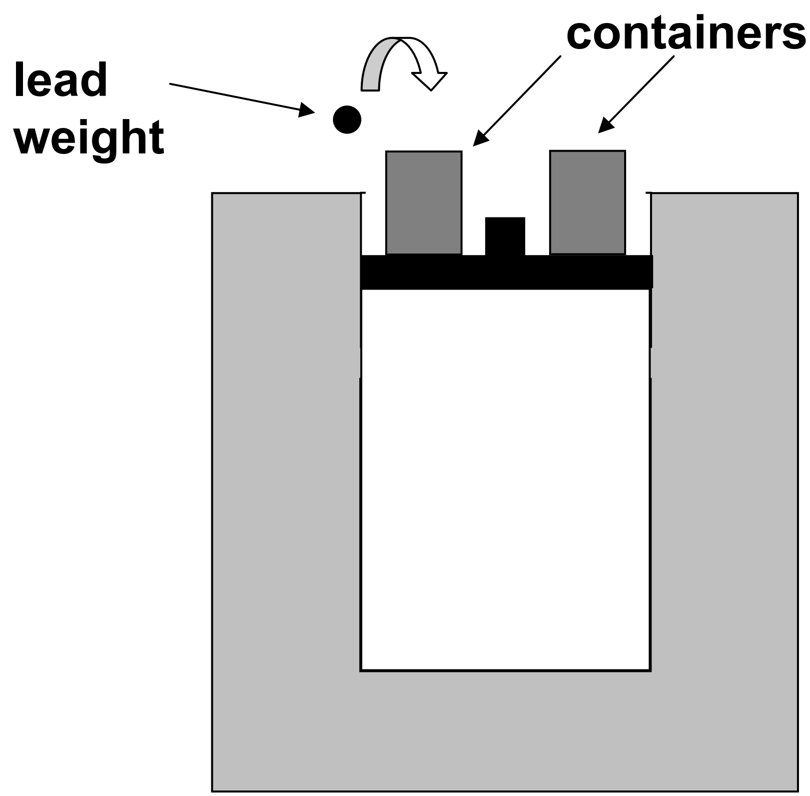
➡ ***Additional questions showed that 50% of the students did not know that some energy was transferred away from gas during expansion.***

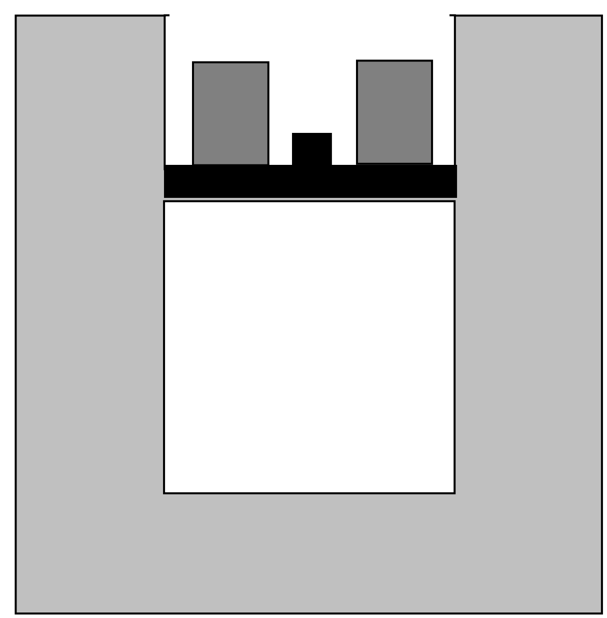
Now, empty containers are placed on top of the piston as shown.



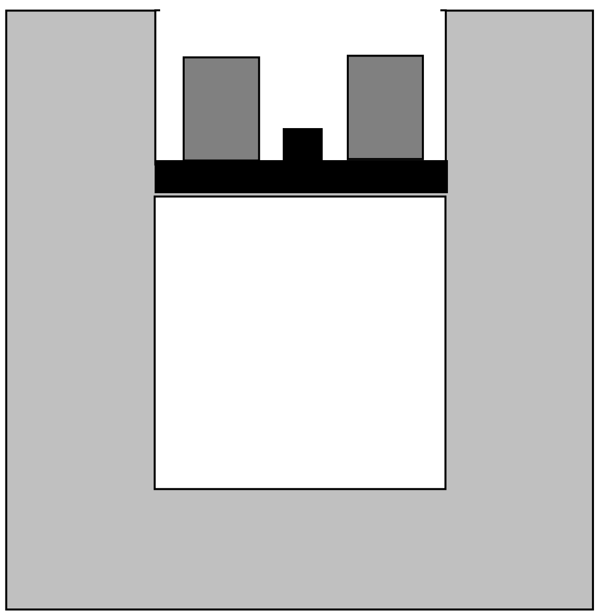
Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly.



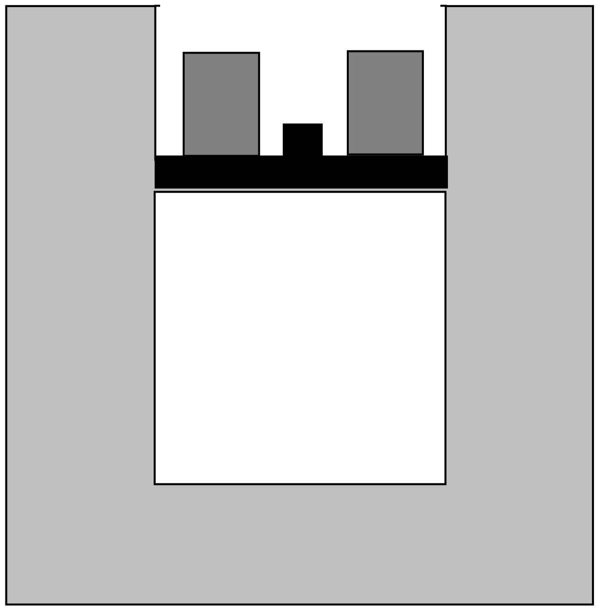

lead
weight
containers

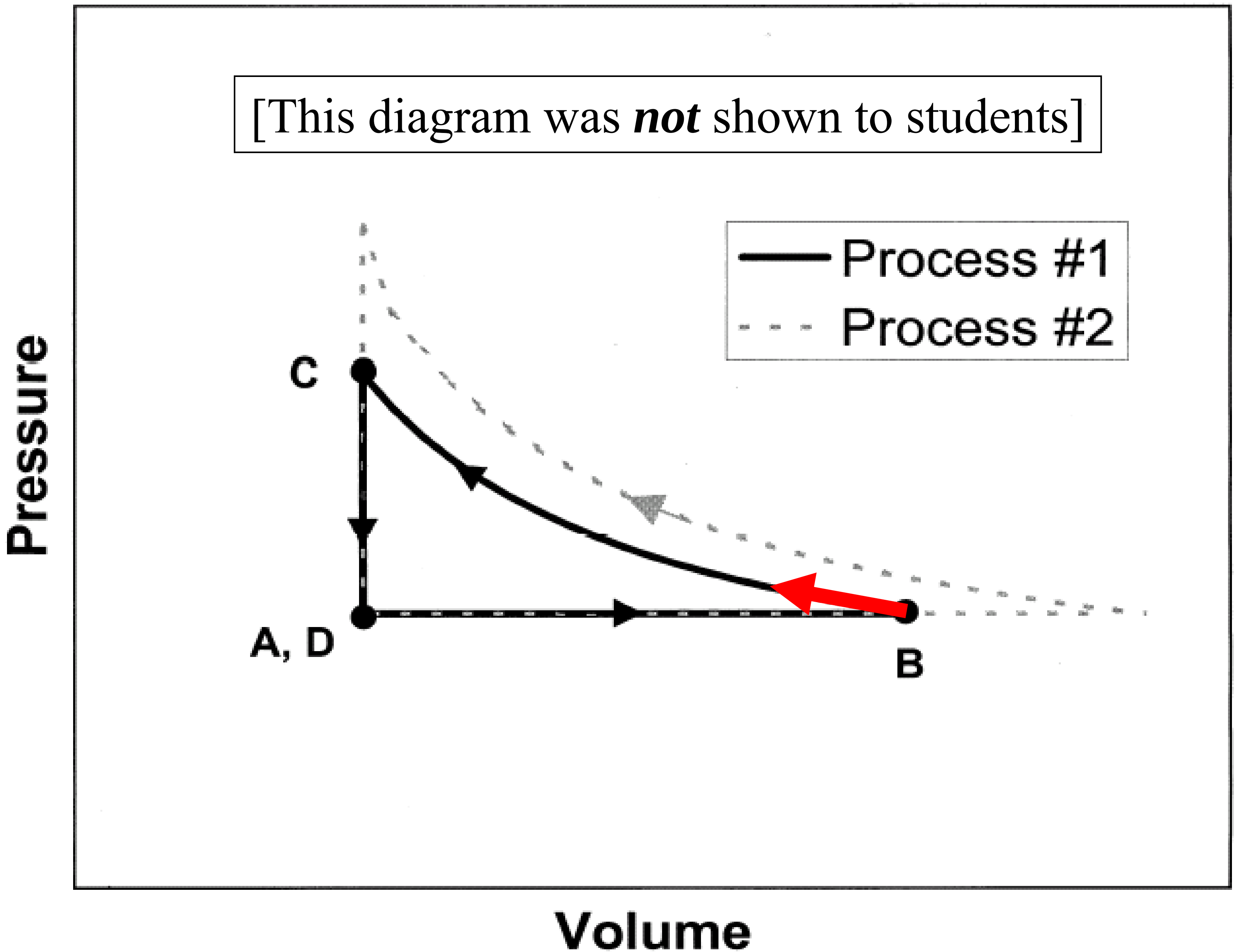


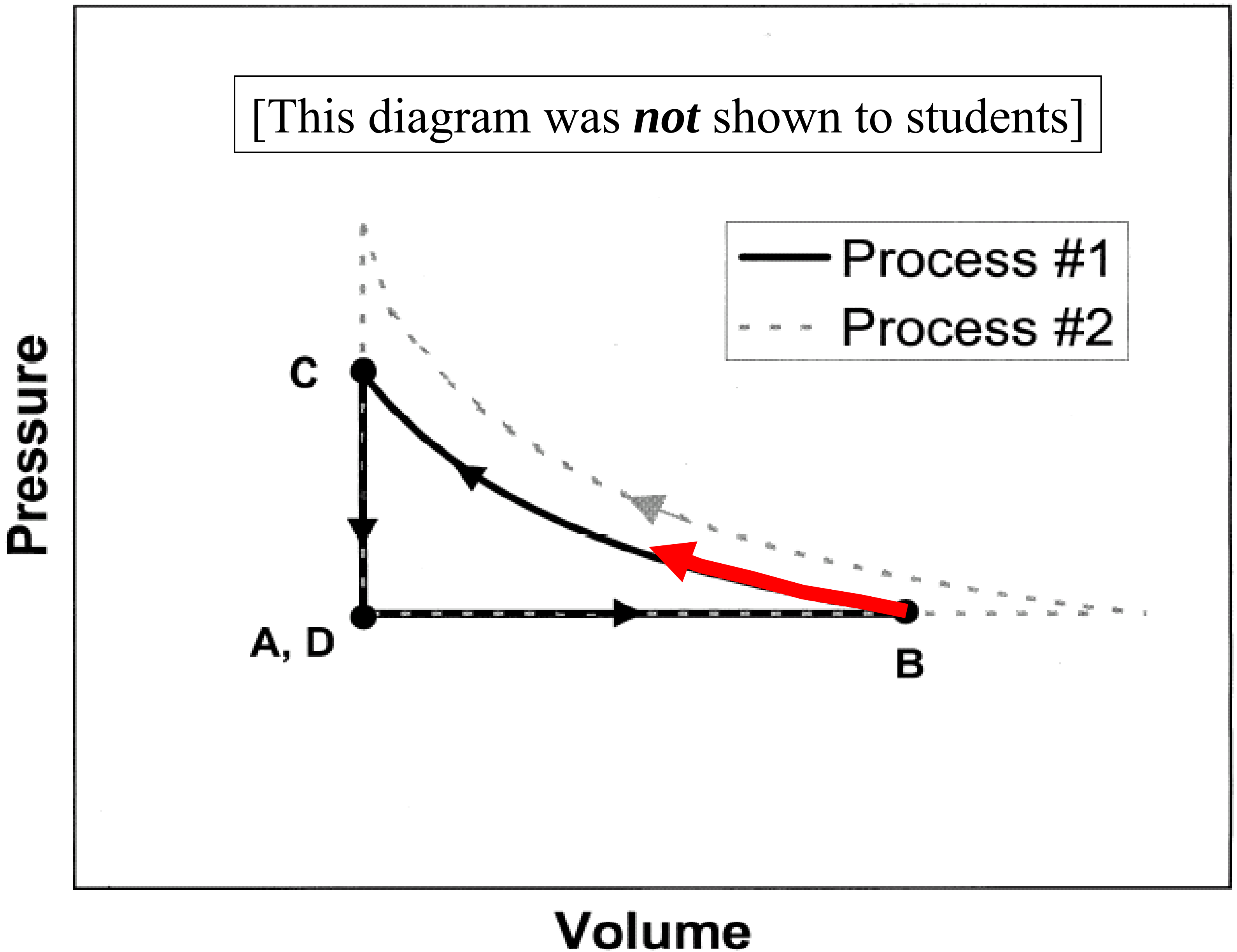
While this happens the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*.



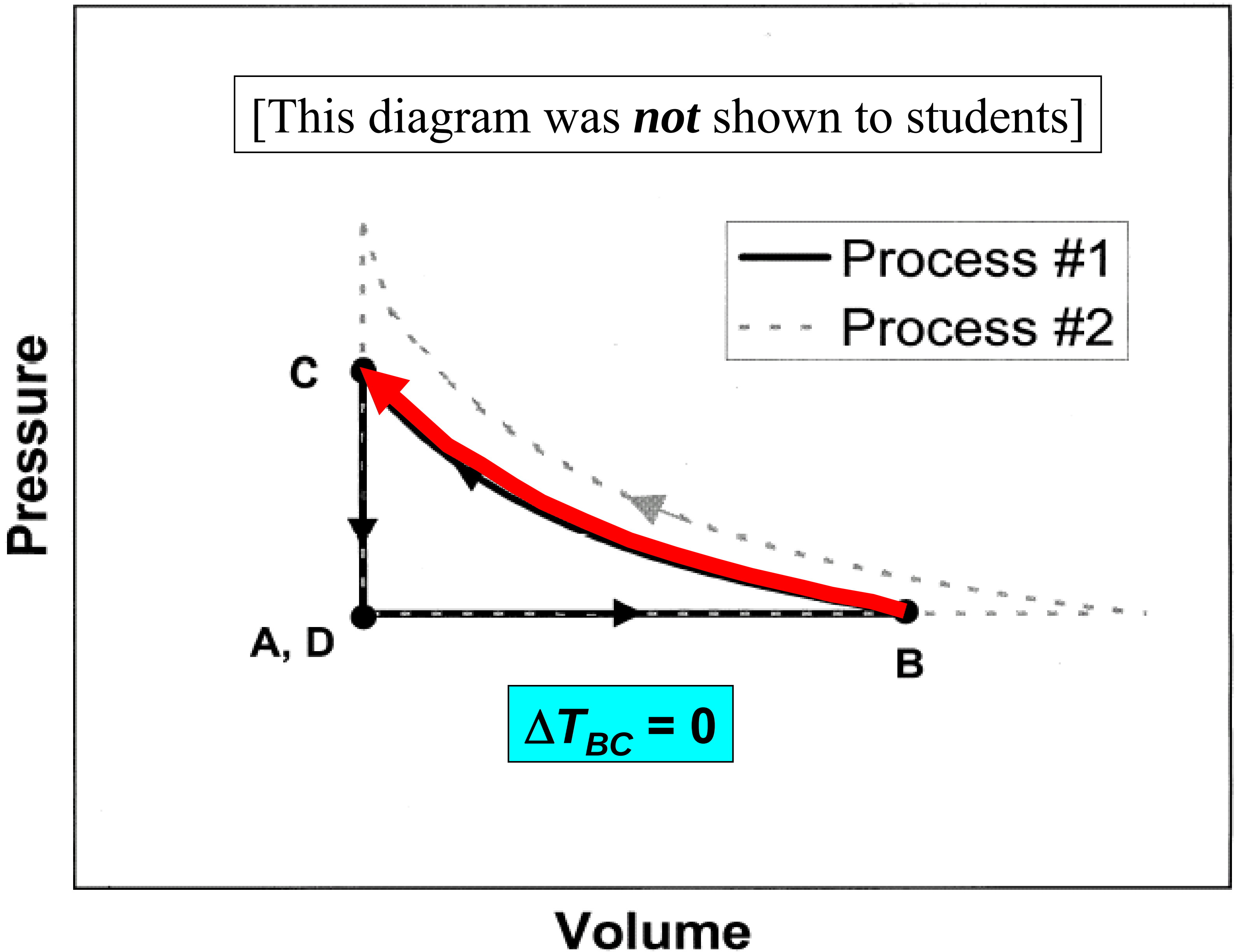
At time ***C*** we stop adding lead weights to the container and the piston stops moving. The piston is now at exactly the same position it was at time ***A*** .

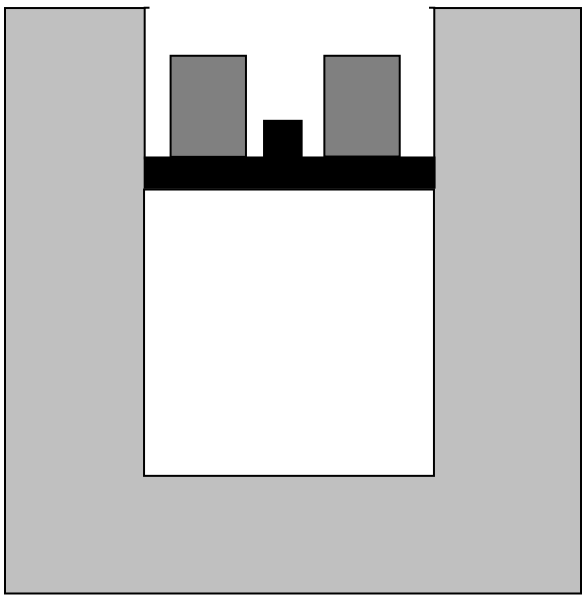



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

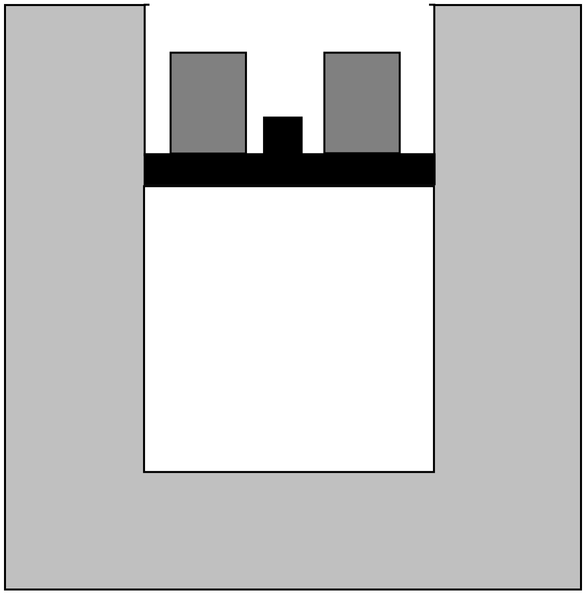


[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume


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



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



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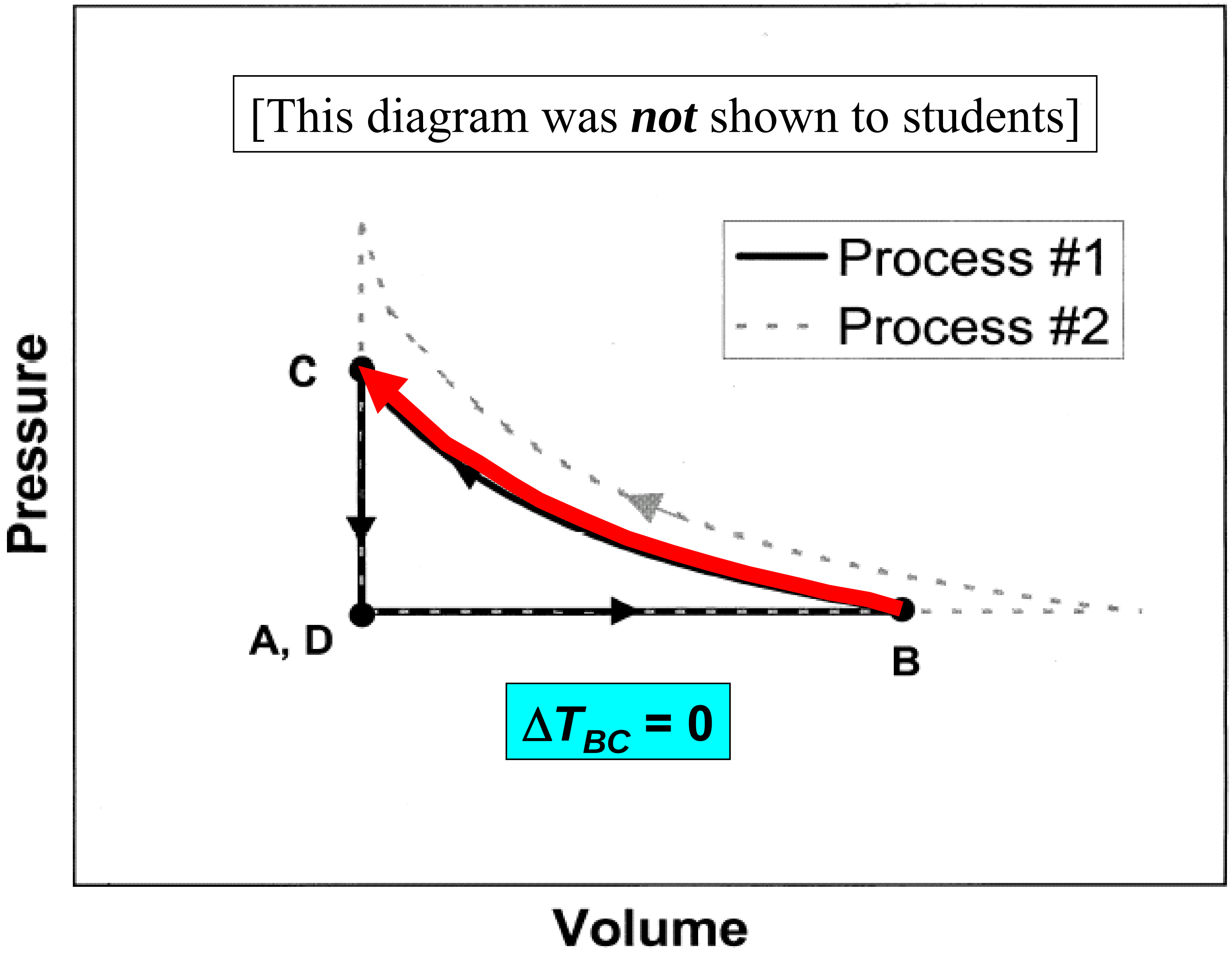
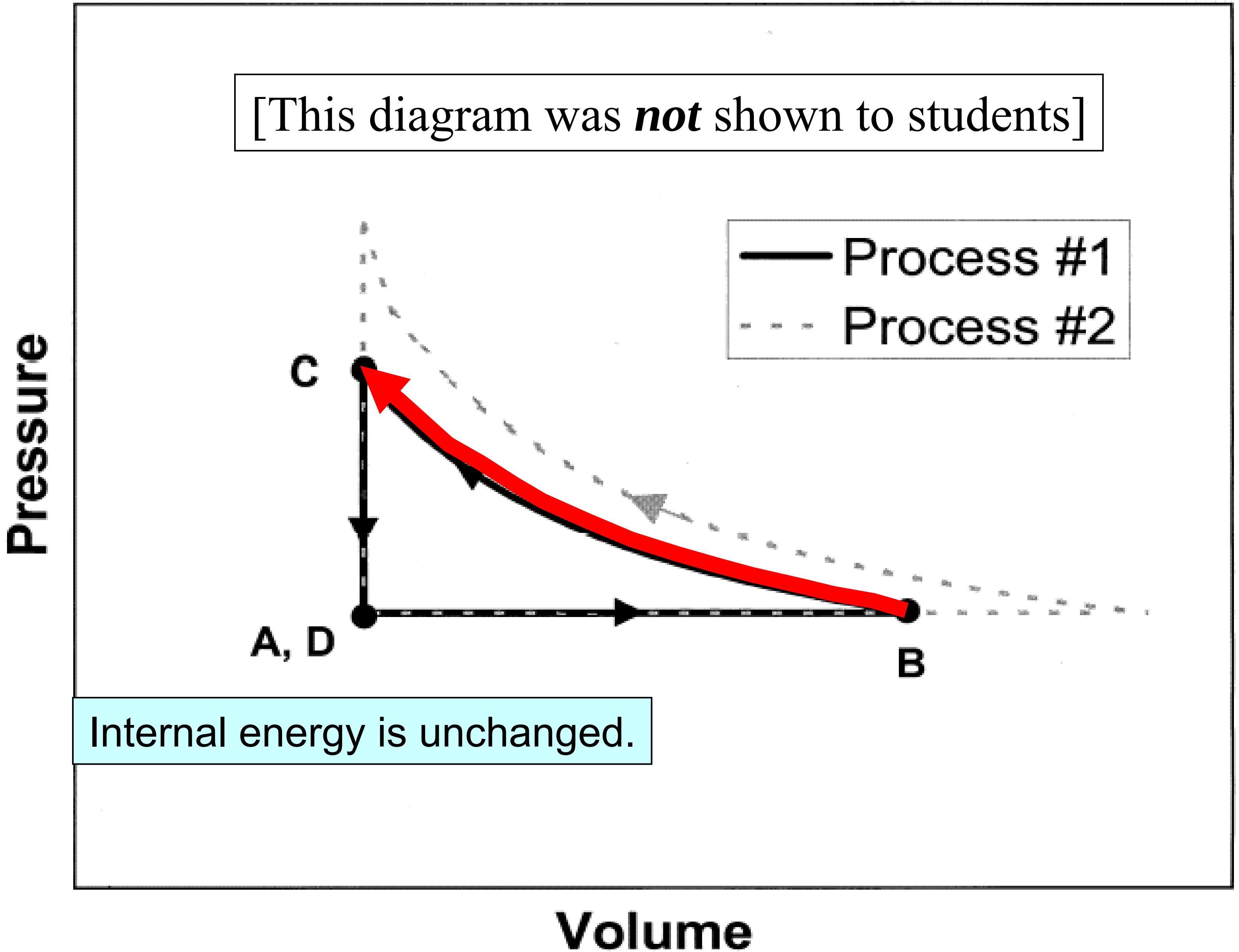
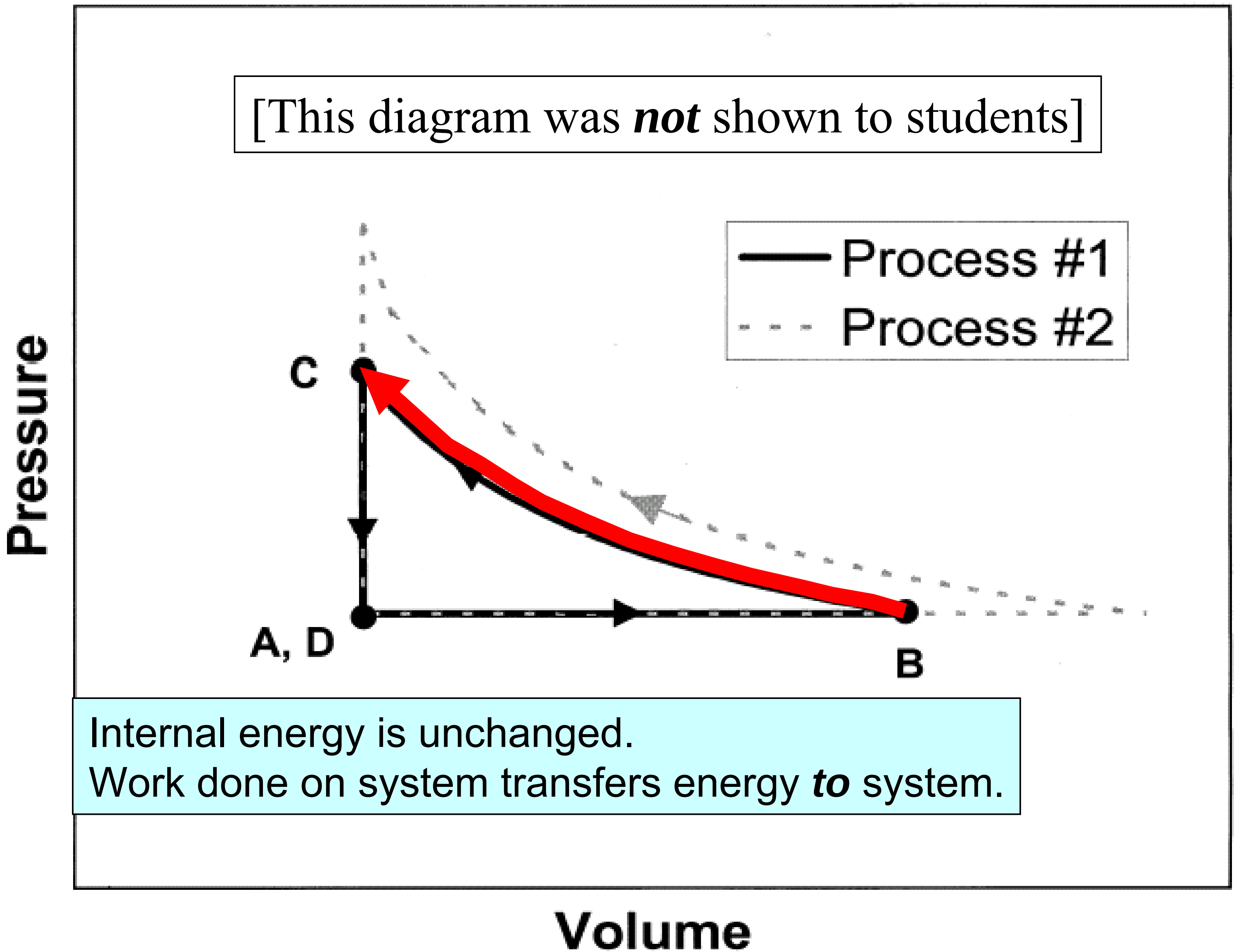


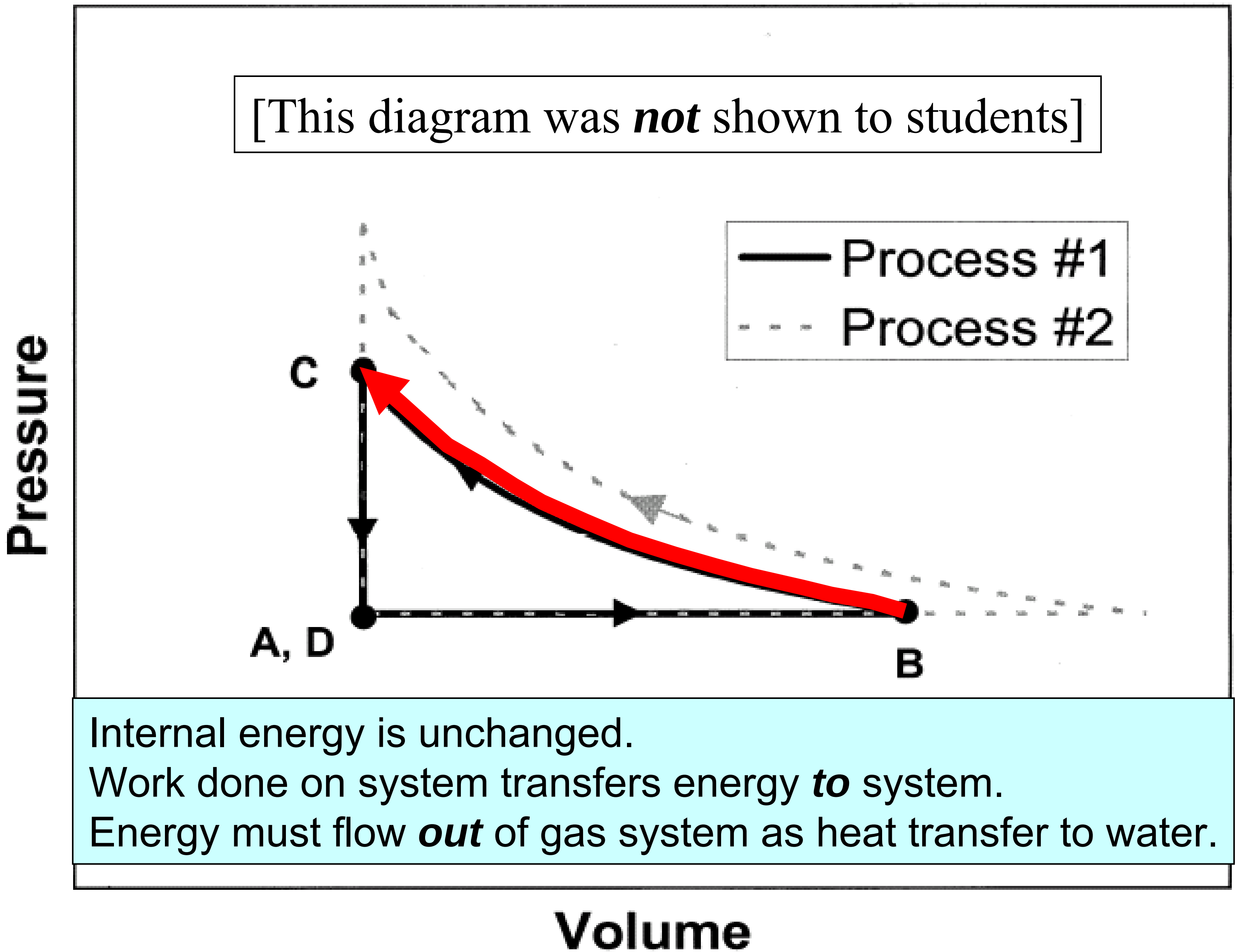
[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
$\Delta T_{BC} = 0$
Pressure
Volume

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

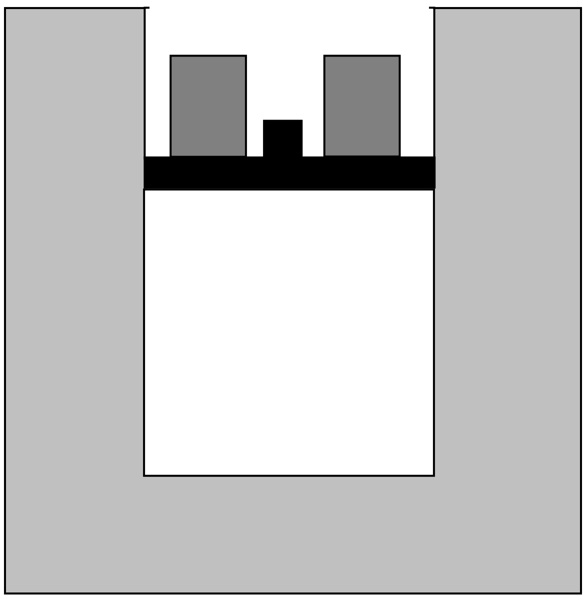


Internal energy is unchanged.

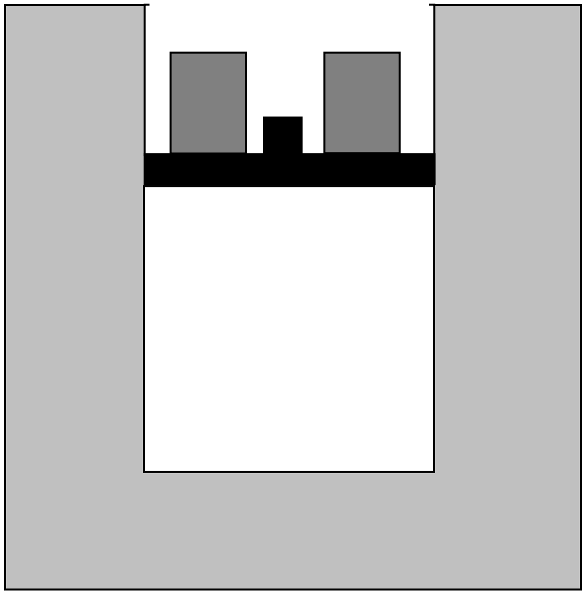

[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume
Internal energy is unchanged.
Work done on system transfers energy ***to*** system.



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



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



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

Results on Question #4

Yes, from gas to water: ***[correct]***

Interview sample *[post-test, N = 32]****: 38%***

2004 Thermal Physics *[pre-test, N = 17]****: 30%***

No [*Q* = 0]:

Interview sample *[post-test, N = 32]****: 59%***

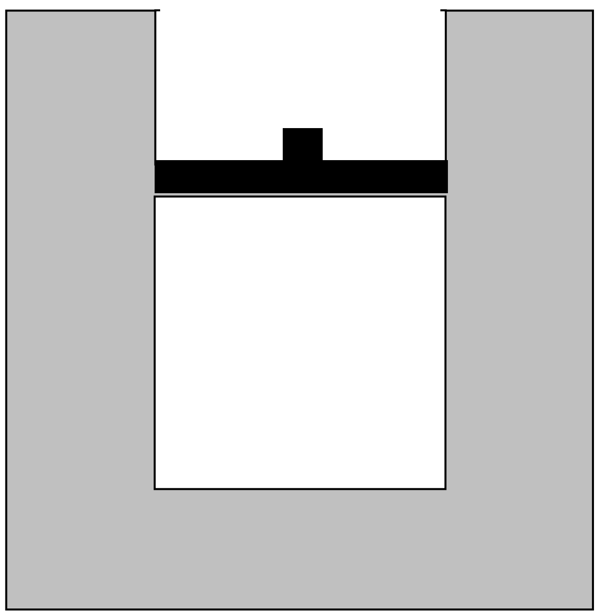
2004 Thermal Physics *[pre-test, N = 16]****: 60%***

Typical Explanation for $Q = 0$:

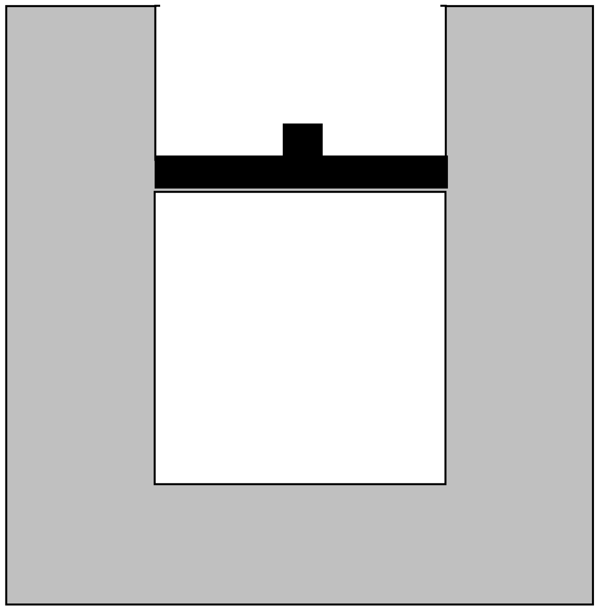
"*No [energy flow], because the temperature of the water does not change*."

Many students also claimed incorrectly that total kinetic energy of ideal gas molecules ***does*** change even when temperature is held *constant*.

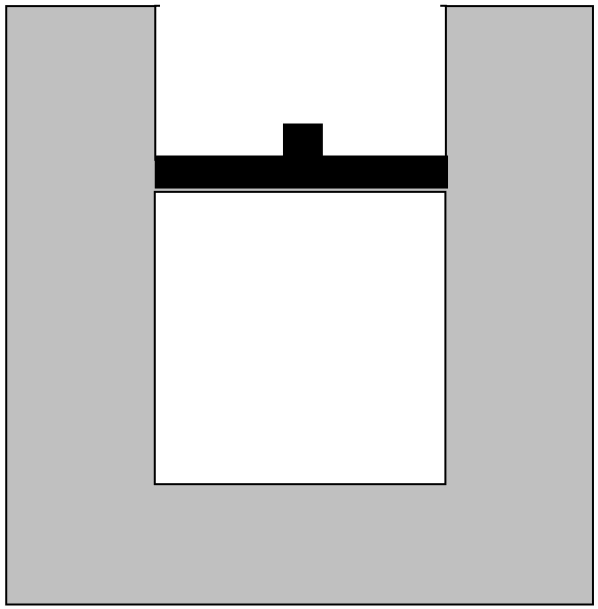
Now, the piston is locked into place so it *cannot move*, and the weights are removed from the piston.



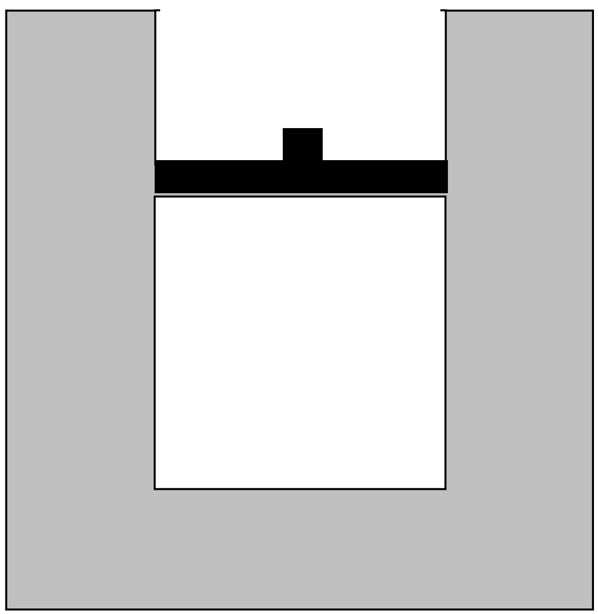
The system is left to sit in the room for many hours.

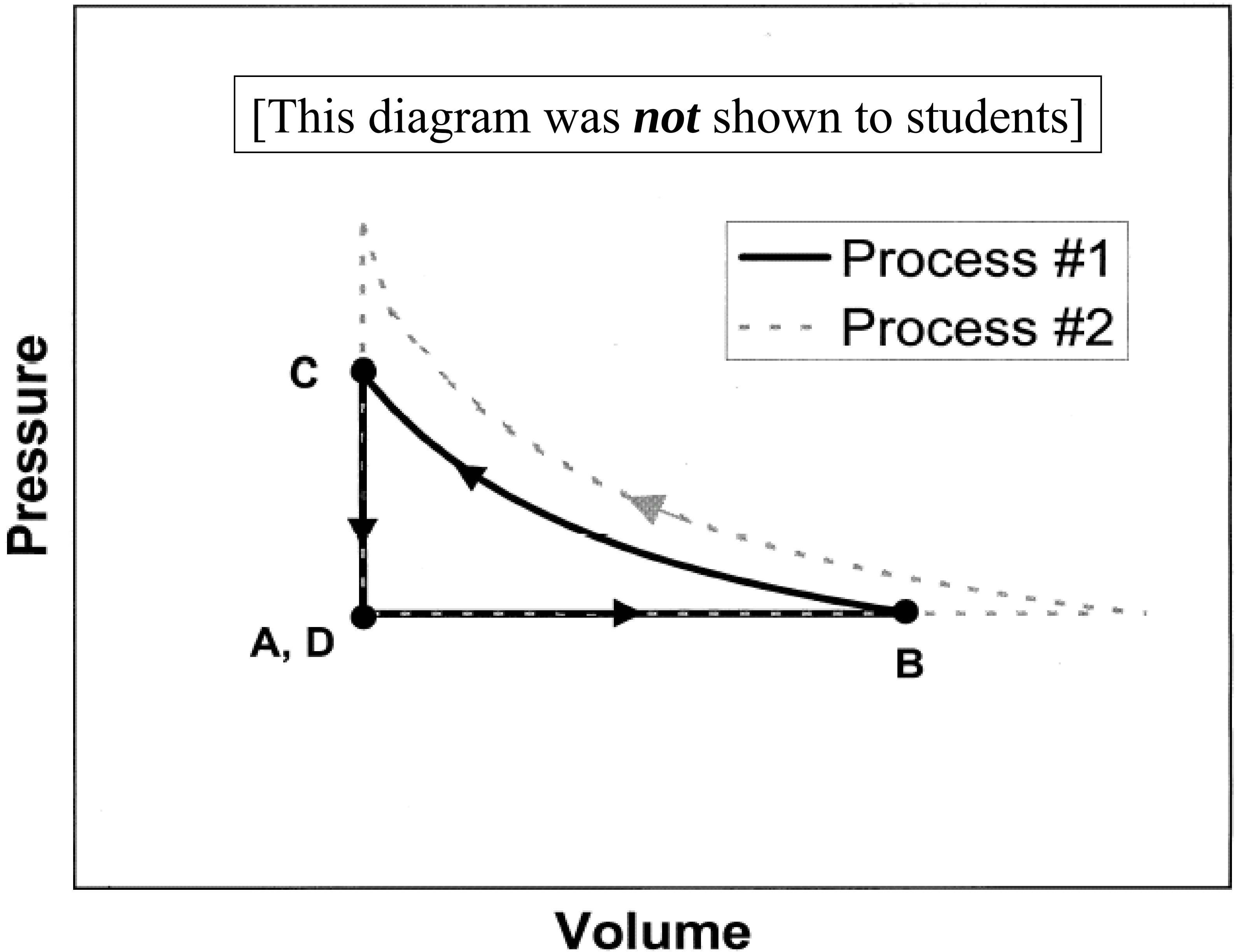


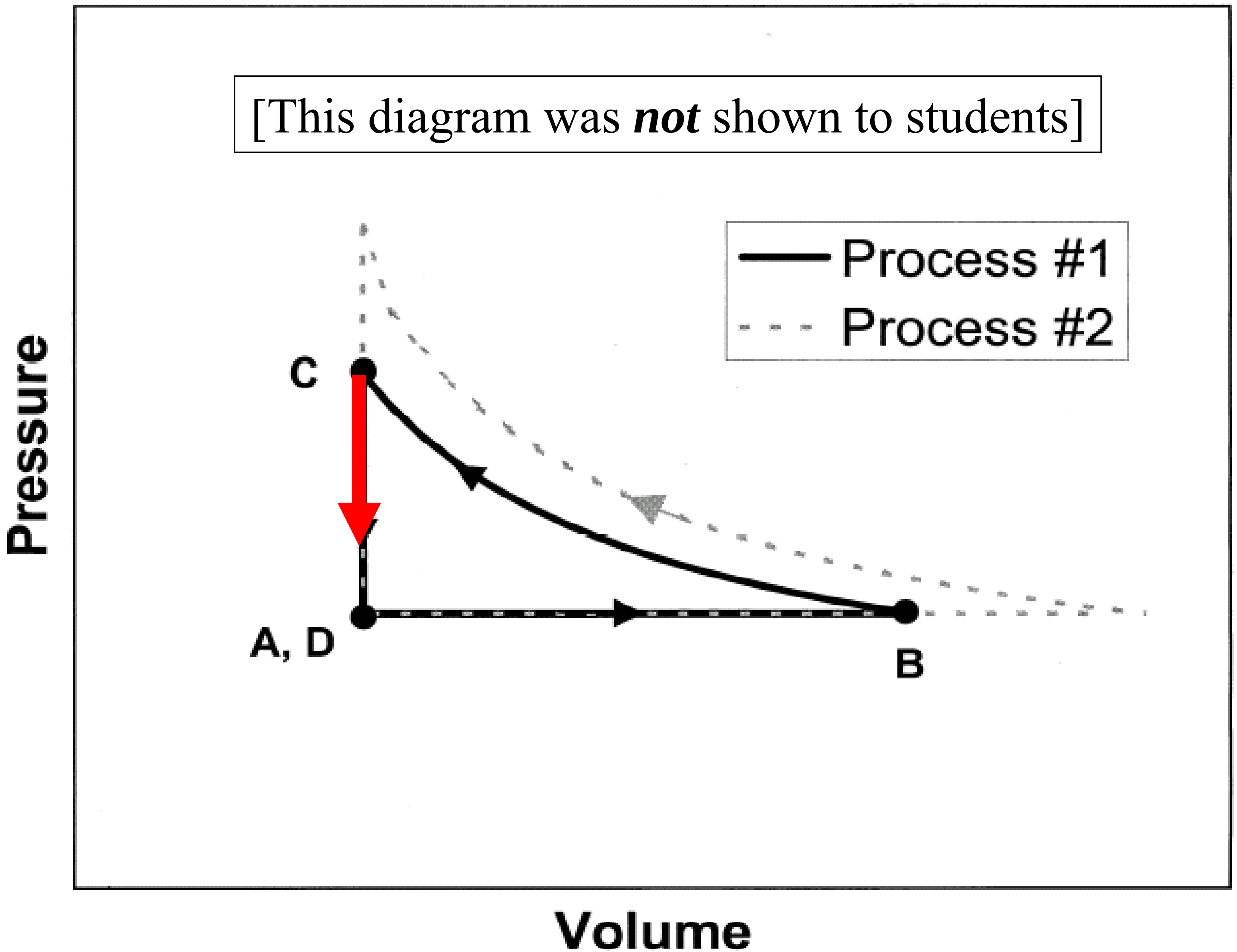
Eventually the entire system cools back down to the same room temperature it had at time ***A***.

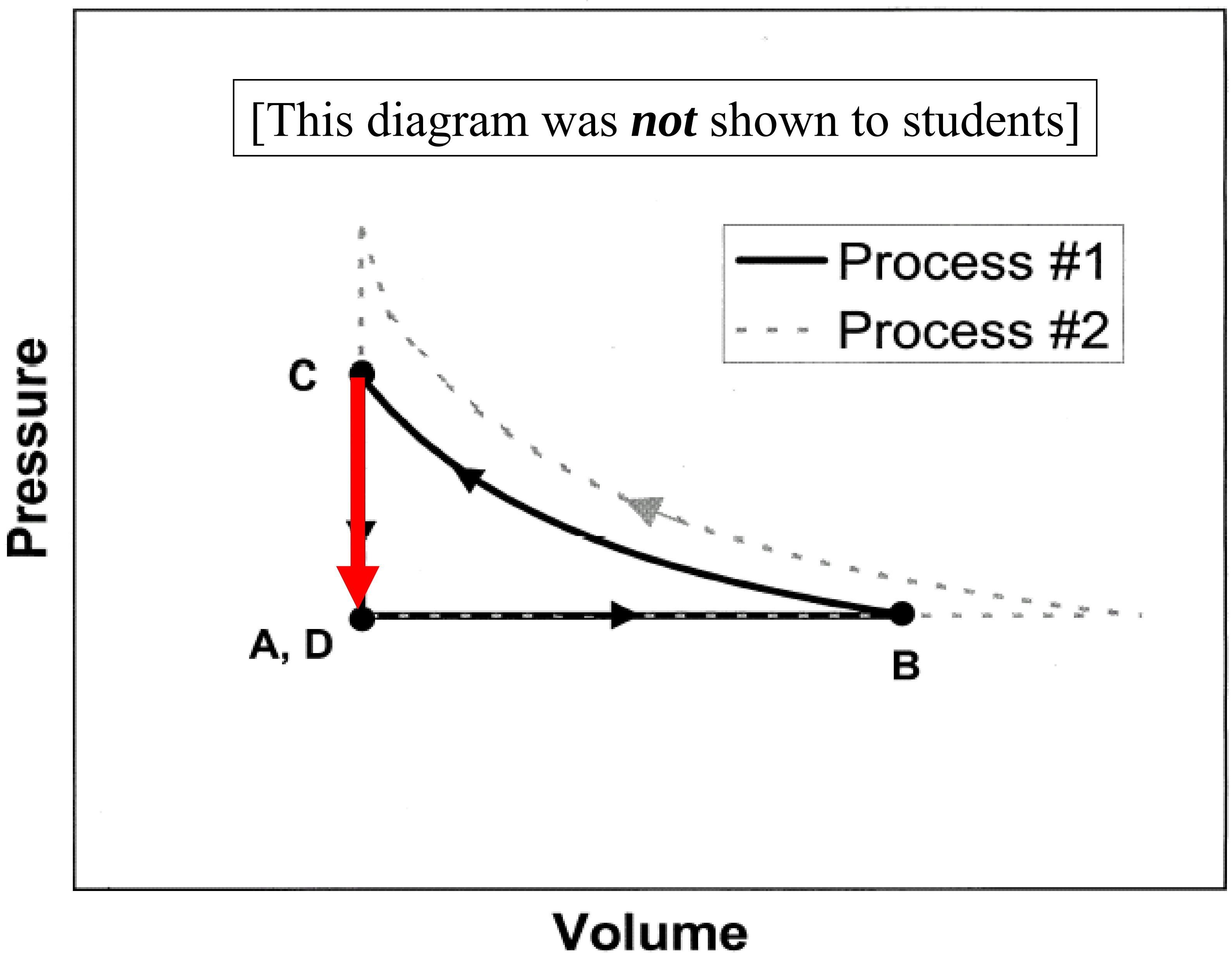


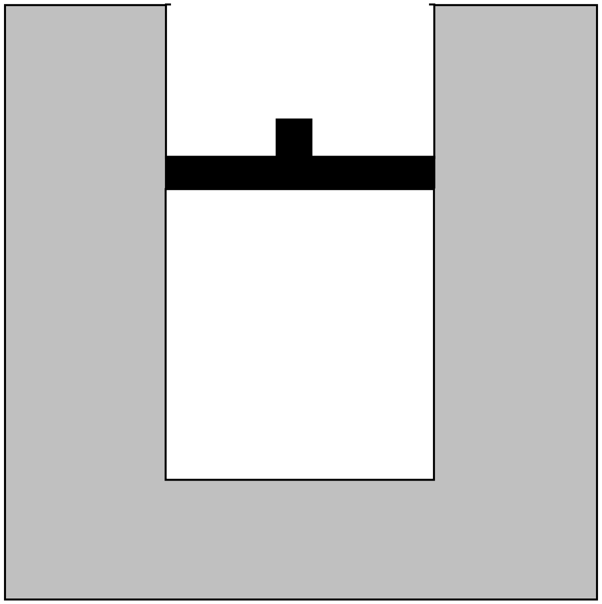
After cooling is complete, it is time ***D.***




[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

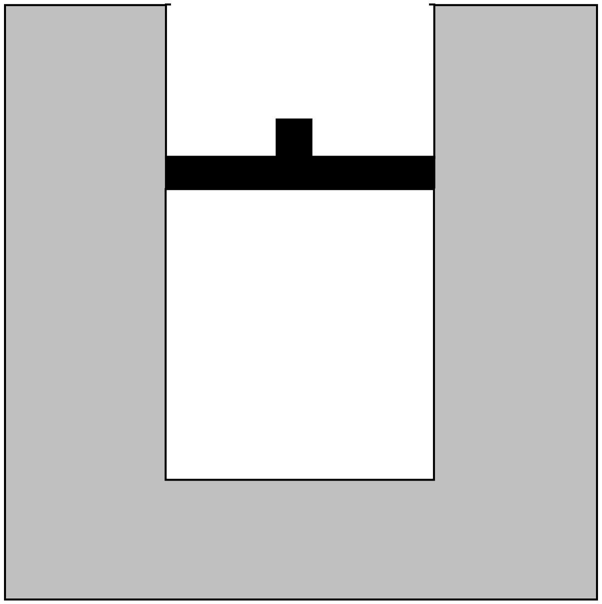

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



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

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

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



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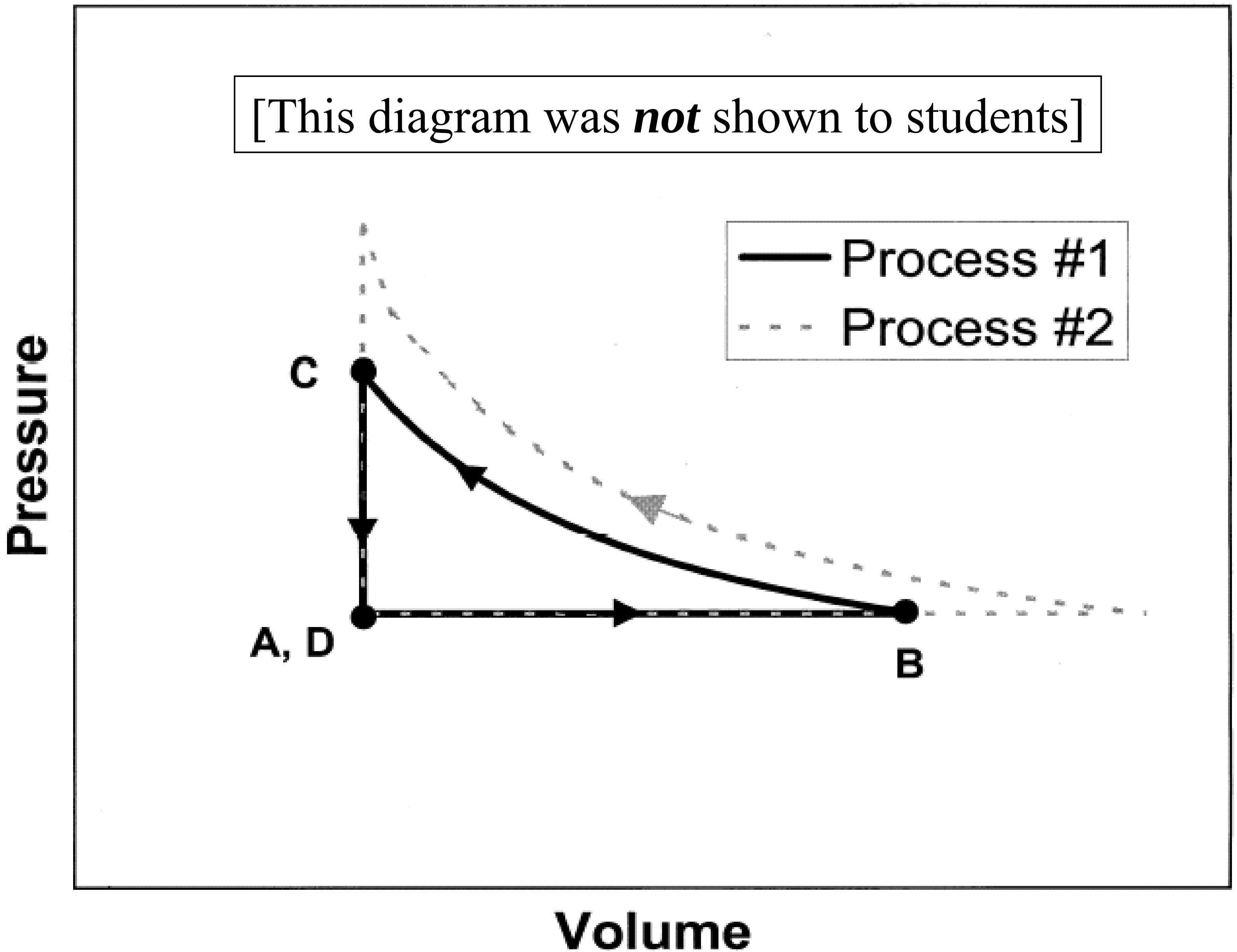
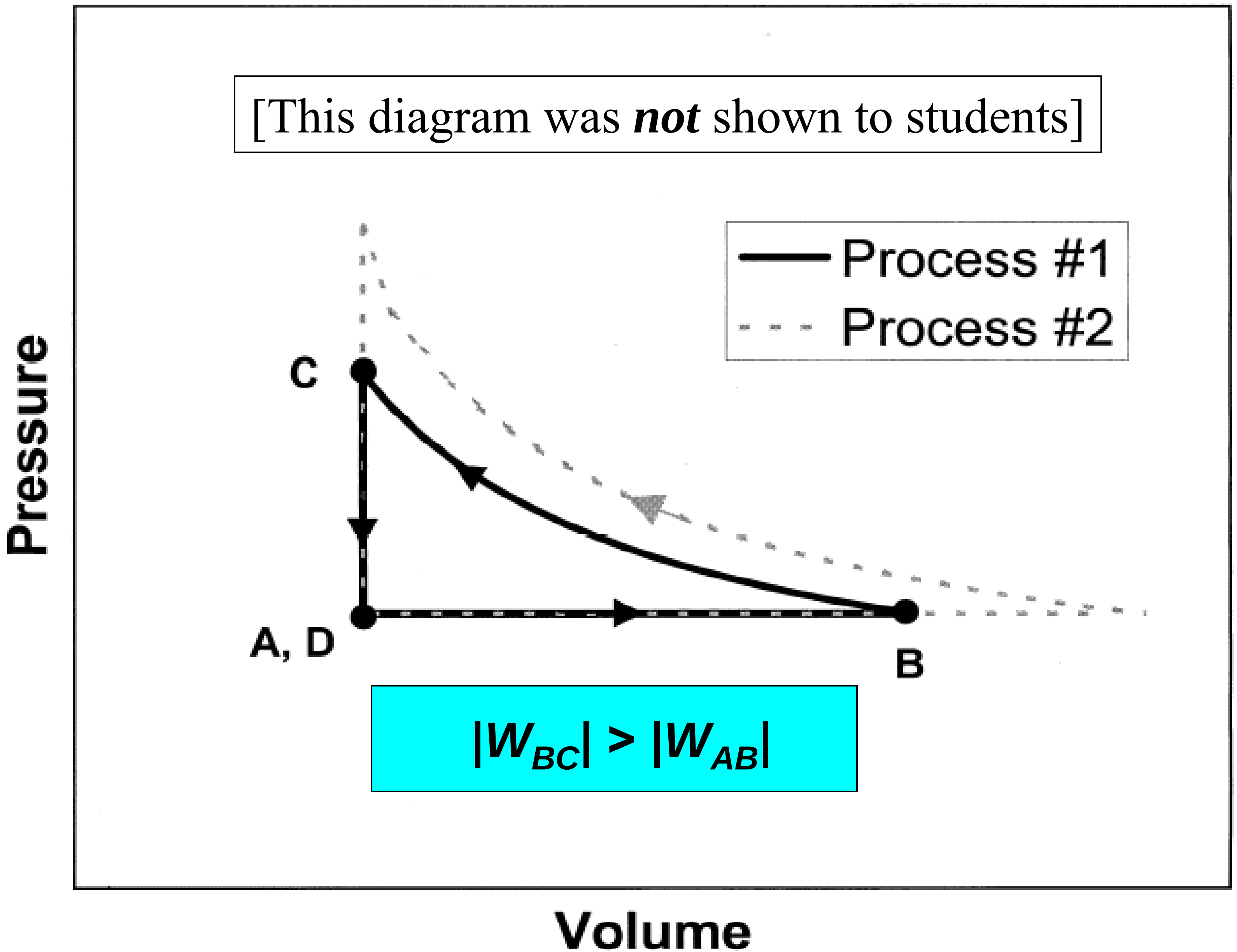
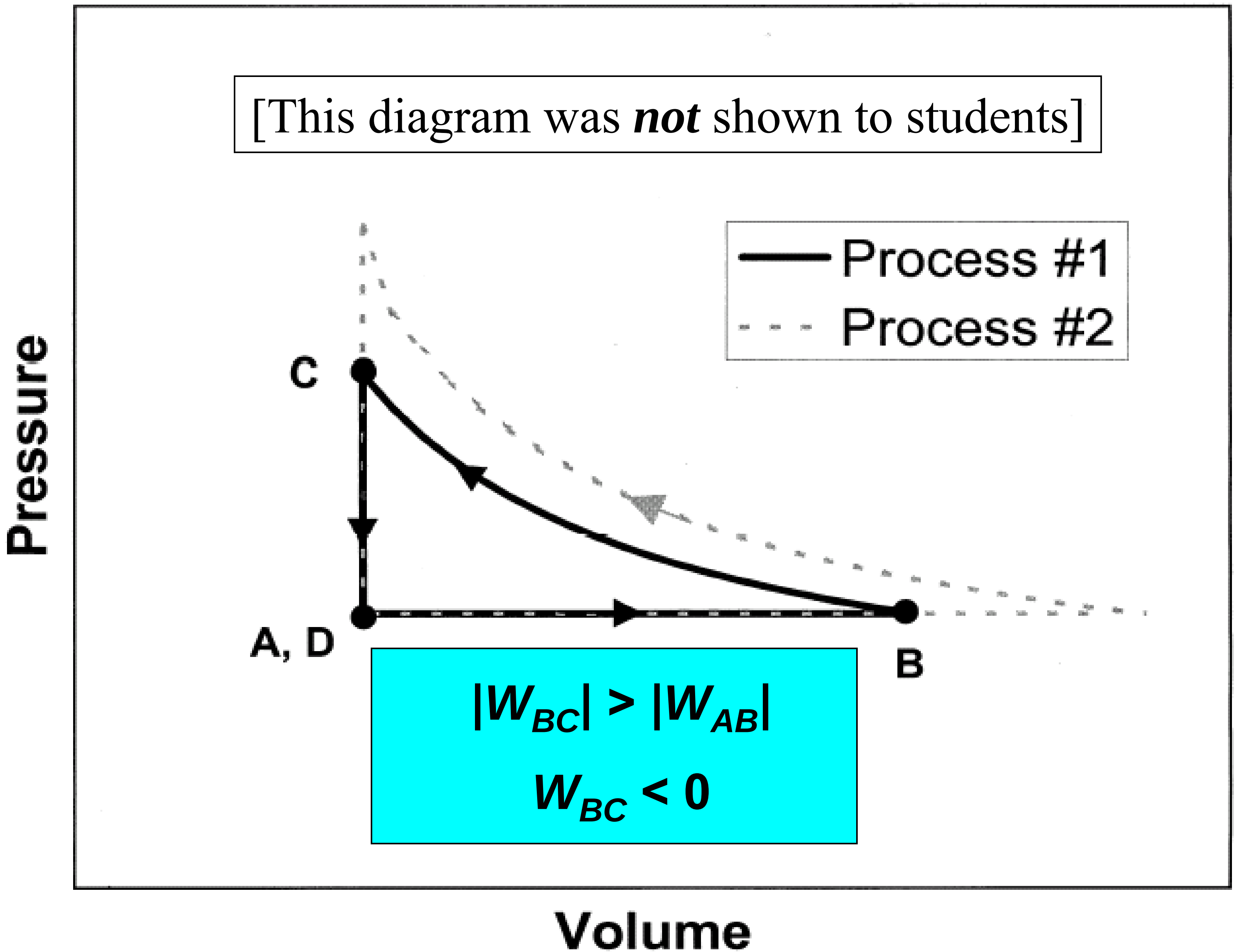
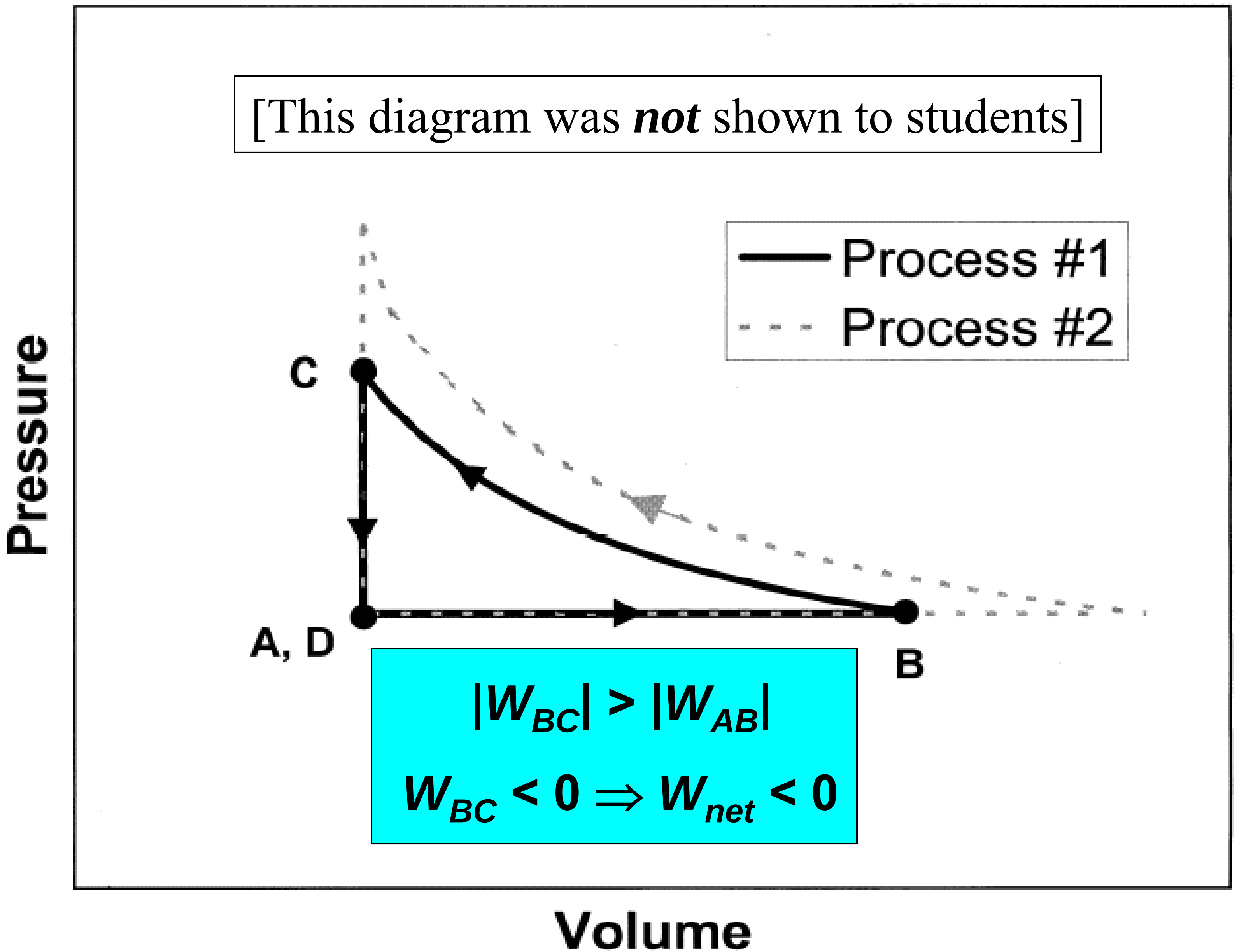
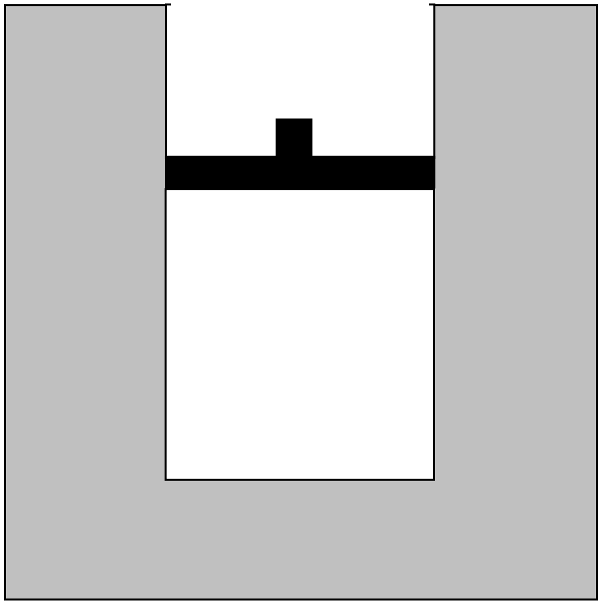

[This diagram was *not* shown to students]
Process #1
Process #2
Pressure
C
A, D
B
Volume


[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
|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 ⇒ W_net < 0
Pressure
Volume



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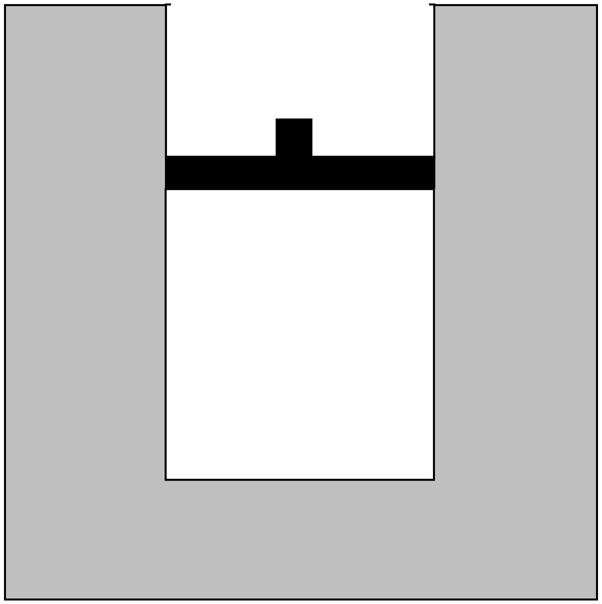

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Results on Question #6 (i)

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

Interview sample *[post-test, N = 32]****: 19%***

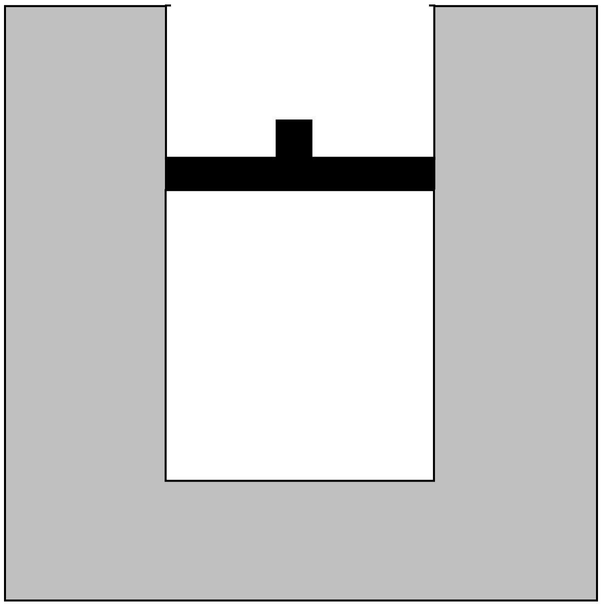
2004 Thermal Physics *[pre-test, N = 16]****: 10%***

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

Interview sample *[post-test, N = 32]****: 63%***

2004 Thermal Physics *[pre-test, N = 16]****: 45%***

Students argued that $W_{\text{net}} = 0$ since $\Delta V = 0$



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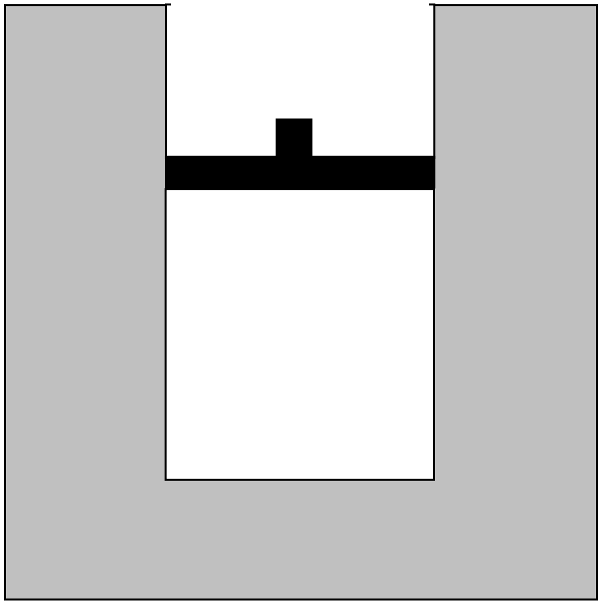

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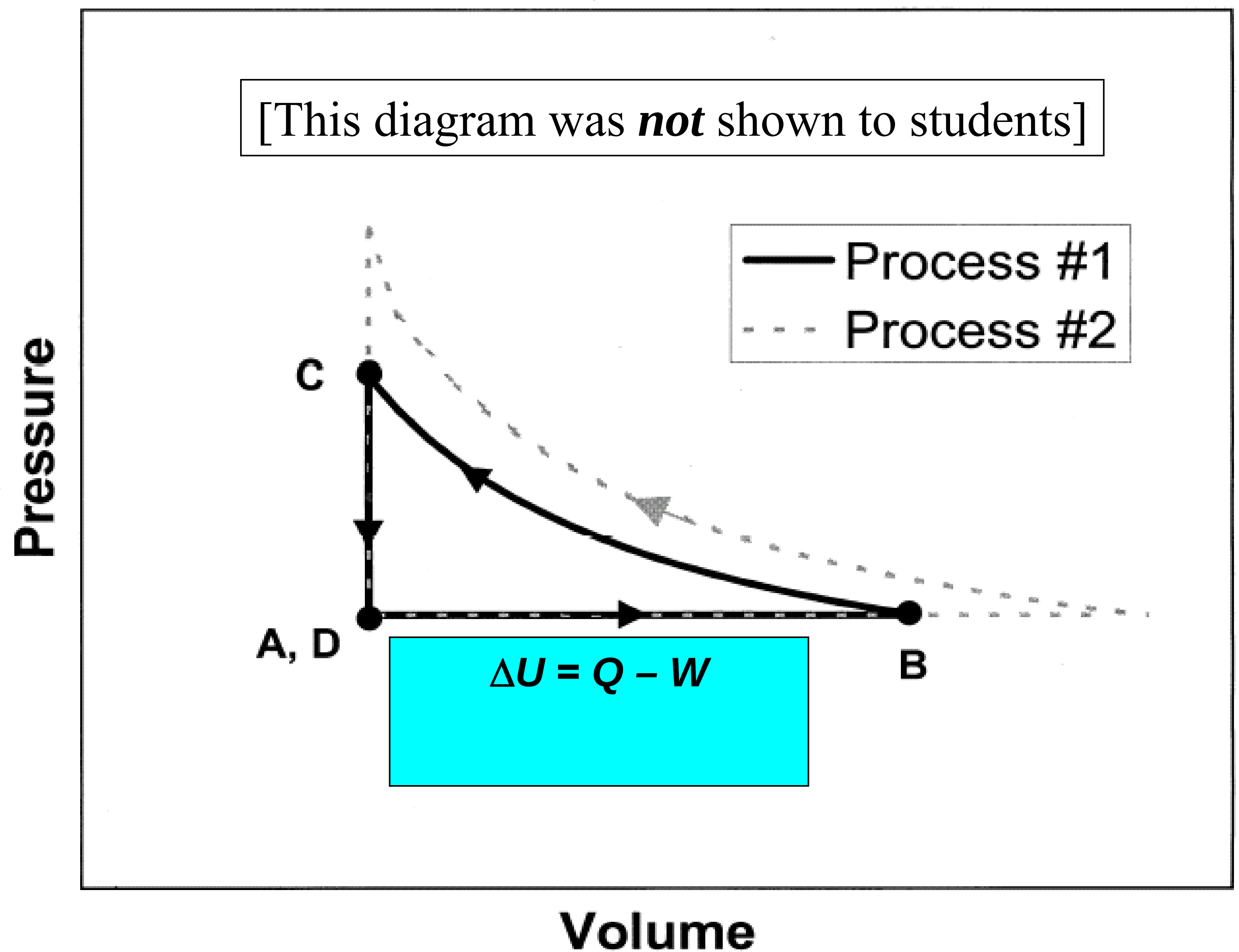
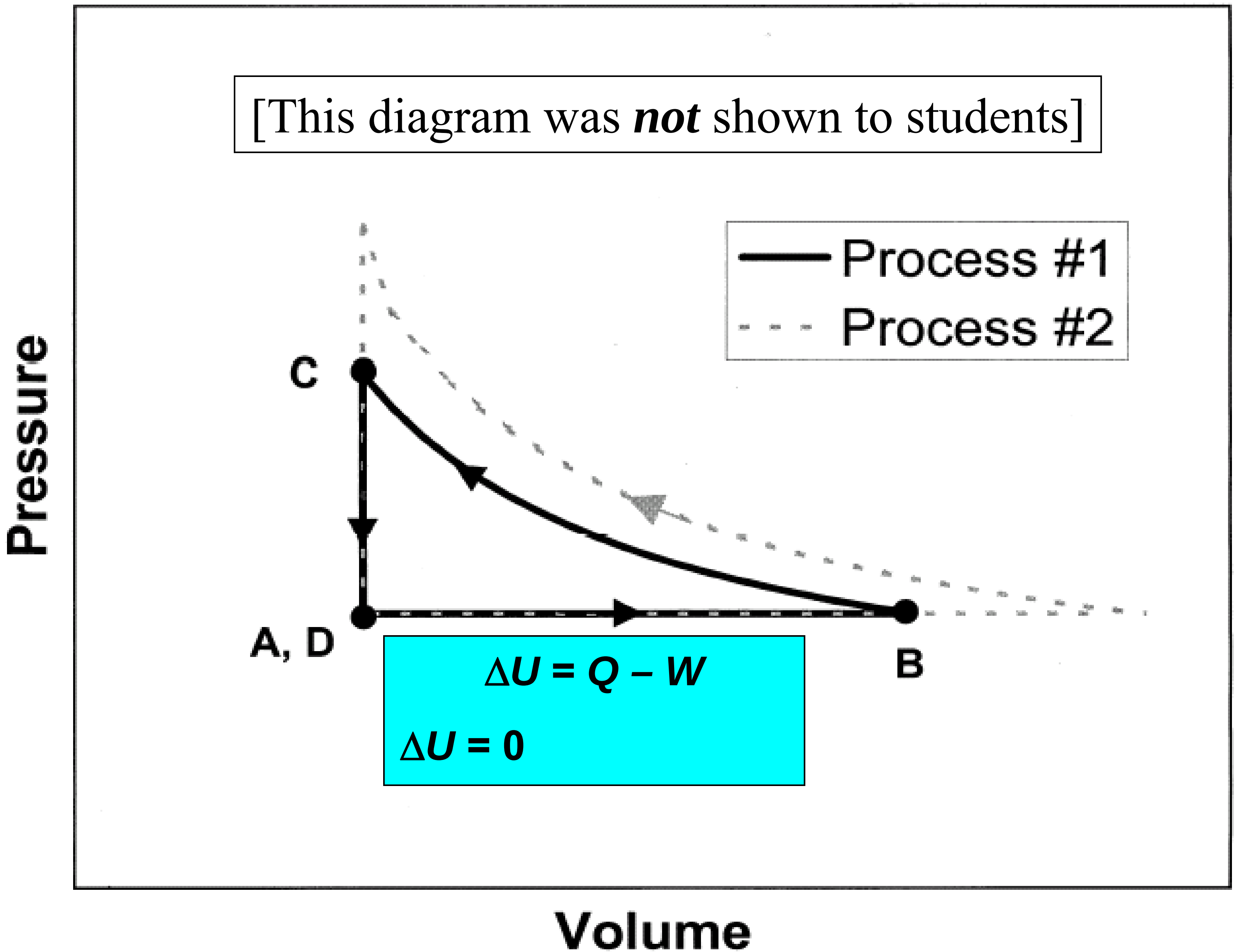
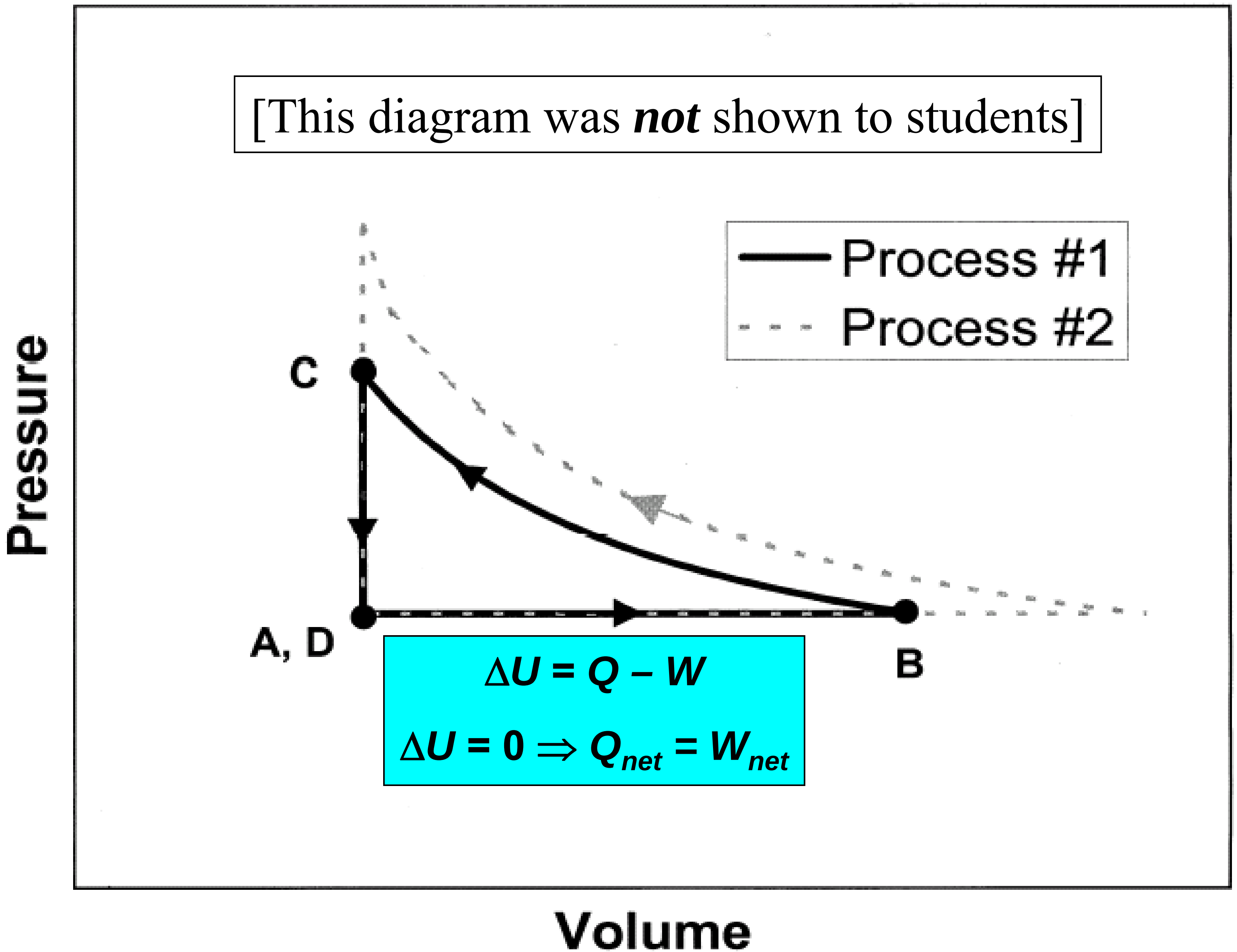


[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
ΔU = Q – W
Pressure
Volume

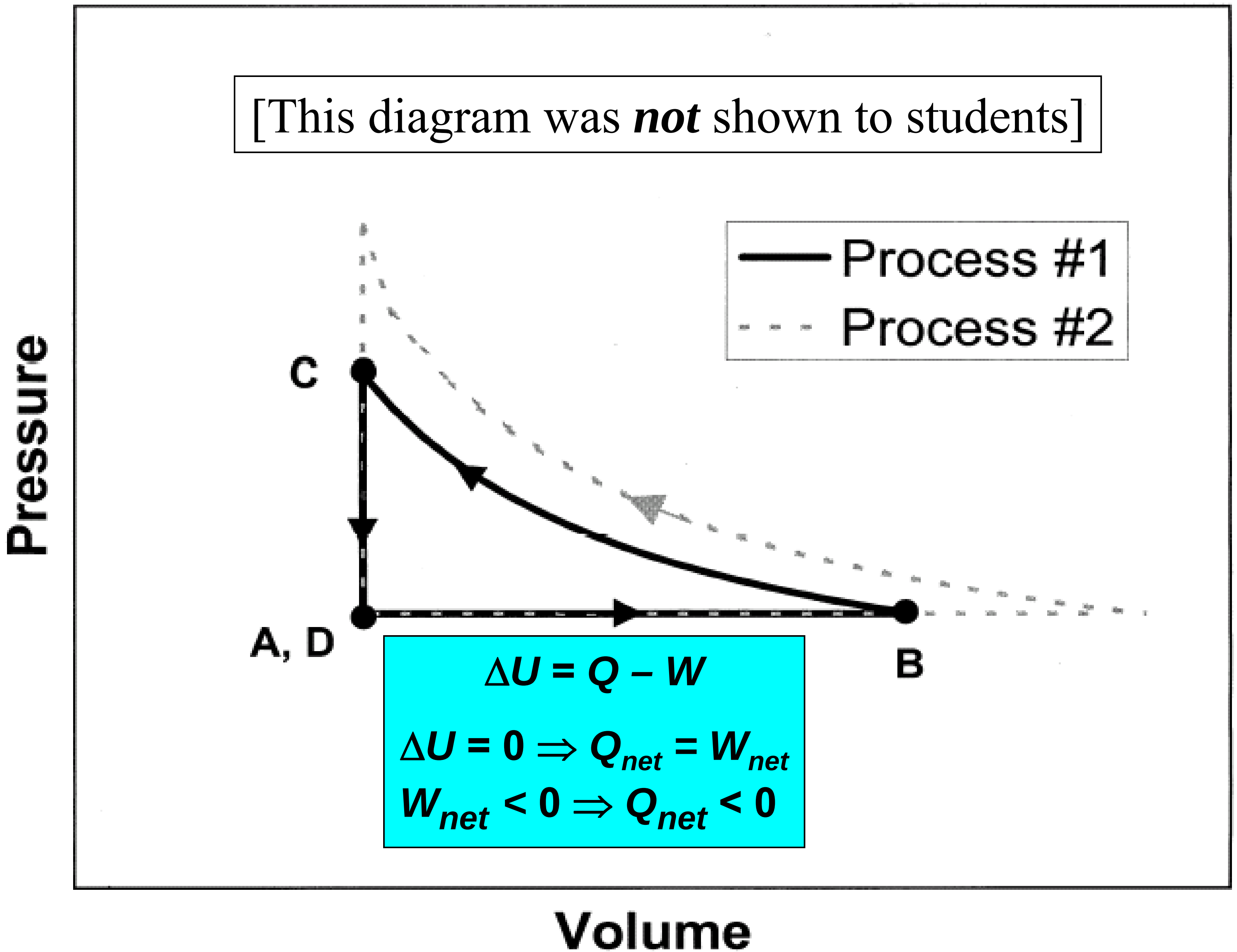

[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
$\Delta U = Q - W$
$\Delta U = 0$
Pressure
Volume

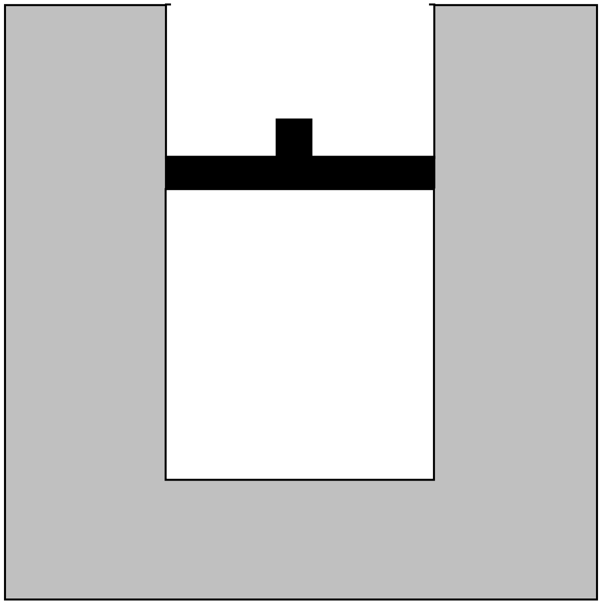
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

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


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



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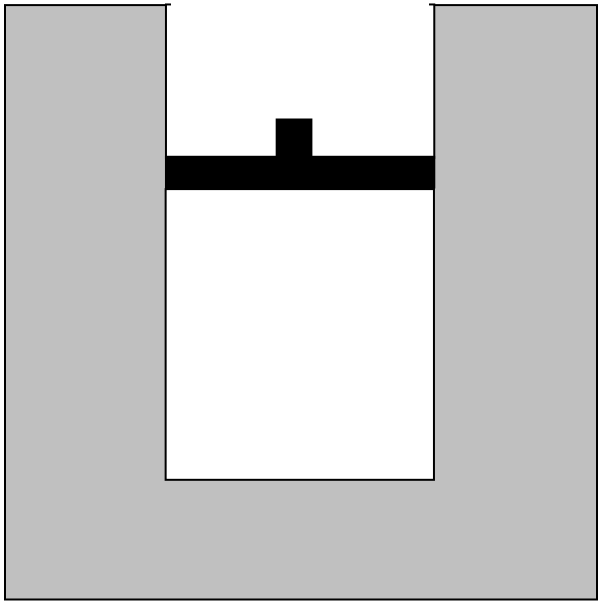


Question #6: Consider ***<u>the entire process</u>*** from time *A* to time *D*.

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

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

Results on Question #6 (ii)

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

Interview sample *[post-test, N = 32]****: 16%***

2004 Thermal Physics *[pre-test, N = 16]****: 20%***

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

Interview sample *[post-test, N = 32]****: 69%***

2004 Thermal Physics *[pre-test, N = 16]****: 80%***

Students argued that $Q_{net} = 0$ since $\Delta T = 0$

Some Strategies for Instruction

Some Strategies for Instruction

- Loverude et al.: Solidify students' concept of work in mechanics context (e.g., positive and negative work);

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

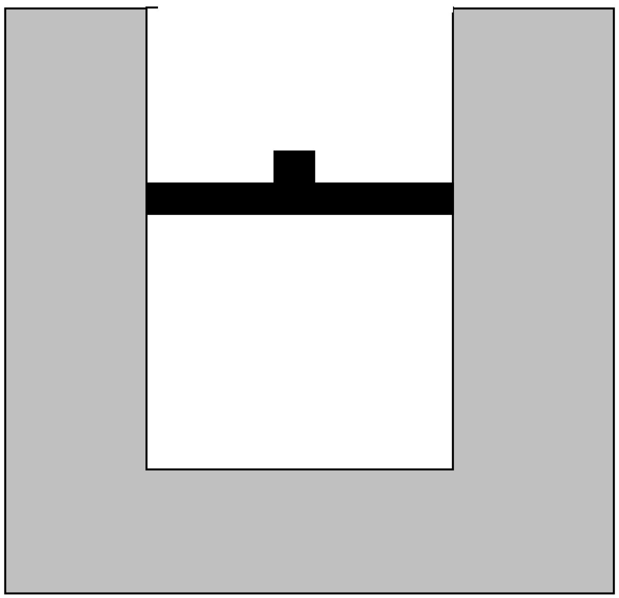
- Guide students to make increased use of *PV*-diagrams and similar representations.
- Practice converting between a diagrammatic representation and a physical description of a given process.
- Use *PV*-diagrams to help solve problems.

Some Strategies for Instruction

- Help to guide students to provide their own justifications for commonly used idealizations such as *thermal reservoir* or *isothermal process.*

Cyclic Process Worksheet

(adapted from interview questions)

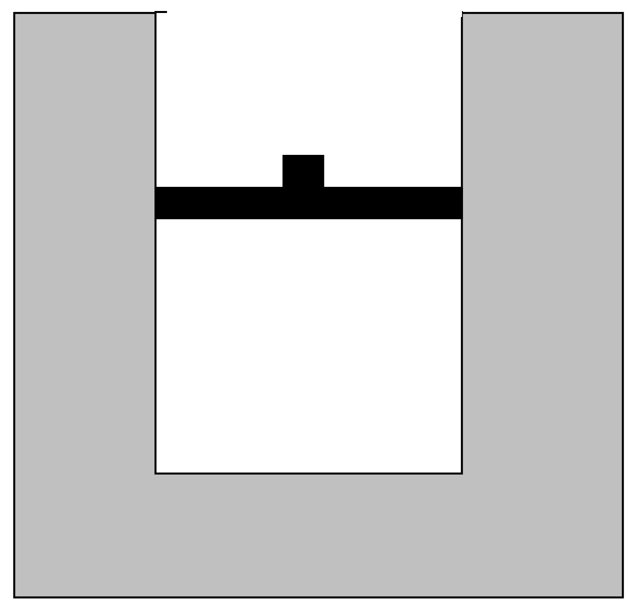


Worksheet Strategy

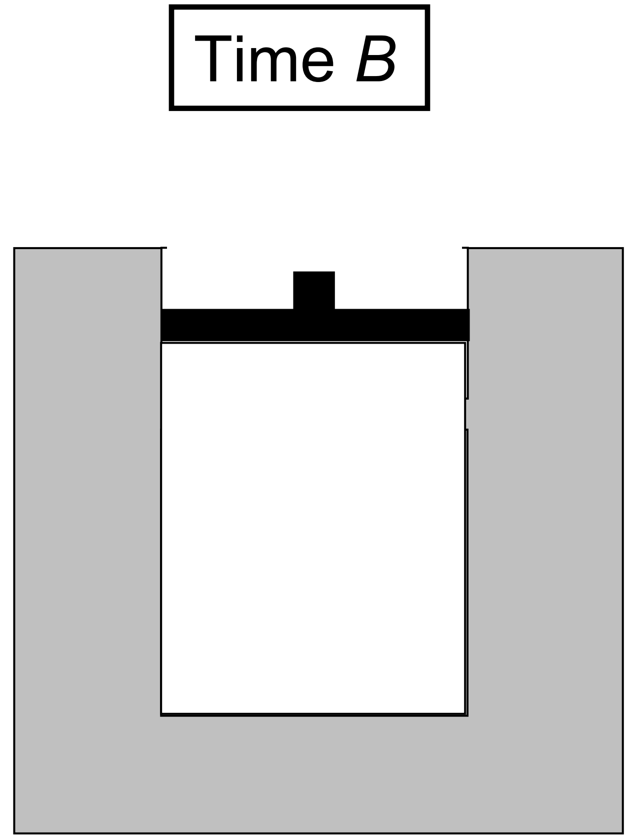
- First, allow students to read description of entire process and answer questions regarding work and heat.

Time *A*

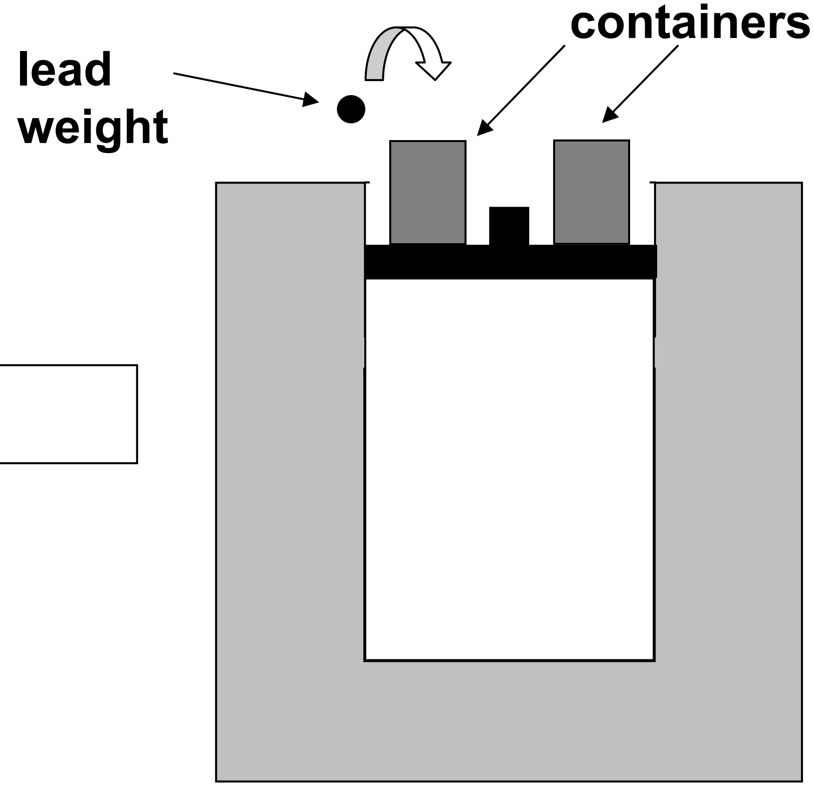
System heated



System heated, piston goes up.



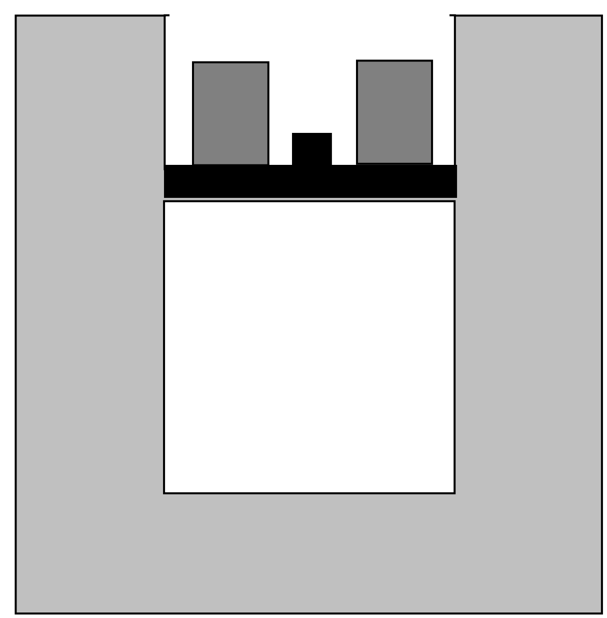
Time *B*



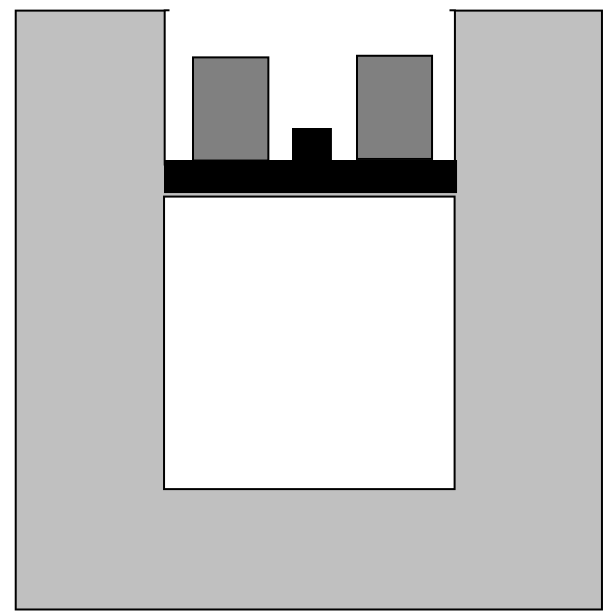
Weights added

Time *C*

Weights added, piston goes down.



Time *C*



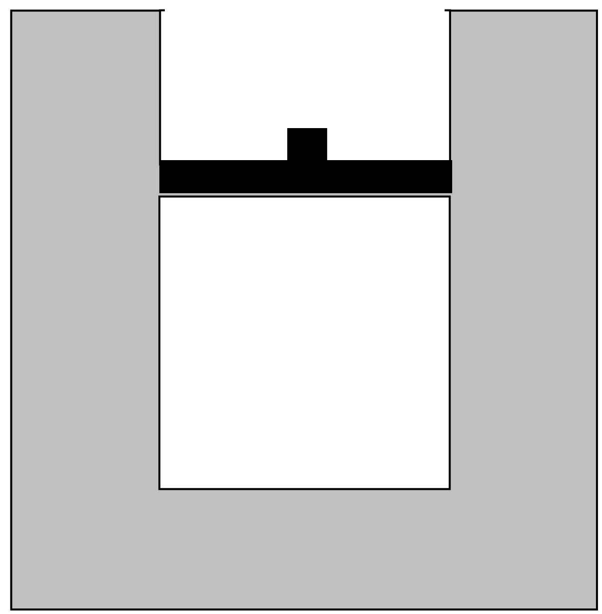
Weights added, piston goes down.

[Temperature remains constant]

Time *C*

Temperature *C*

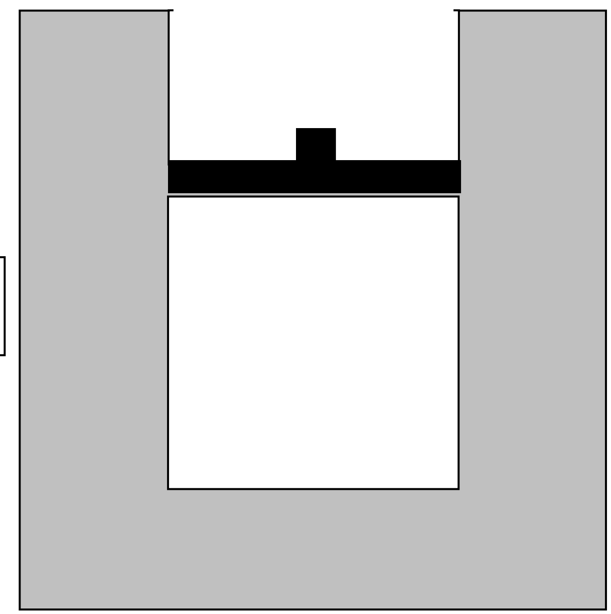
Piston locked

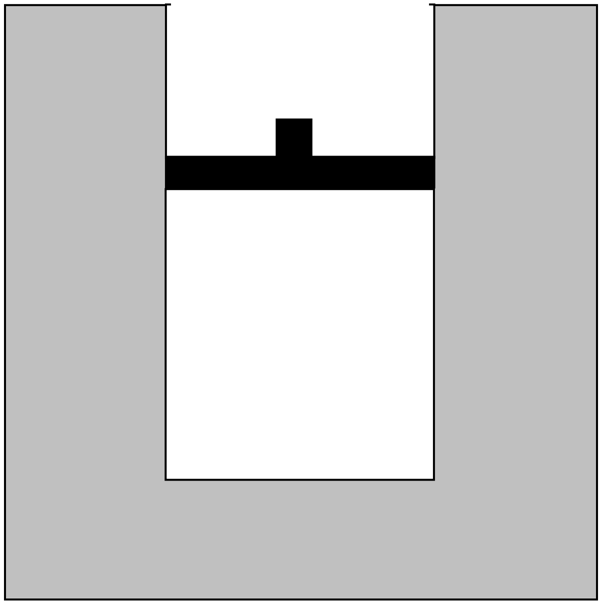


Time *D*

Temperature *D*

Piston locked, temperature goes down.

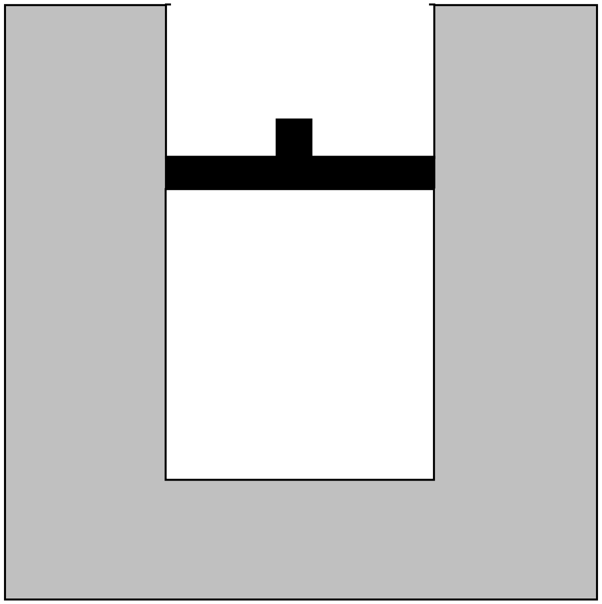




Question #6: Consider ***<u>the entire process</u>*** from time *A* to time *D*.

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

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



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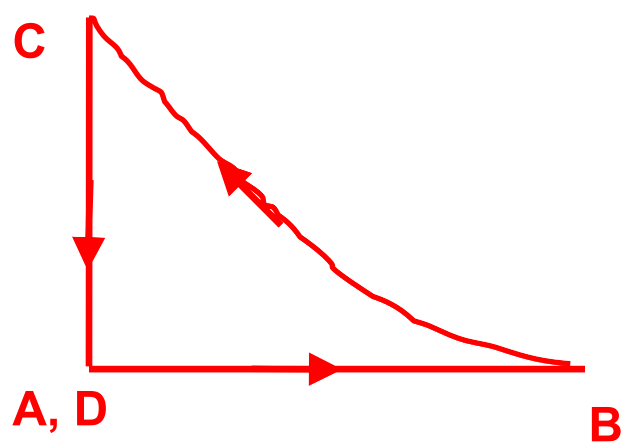
Worksheet Strategy

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

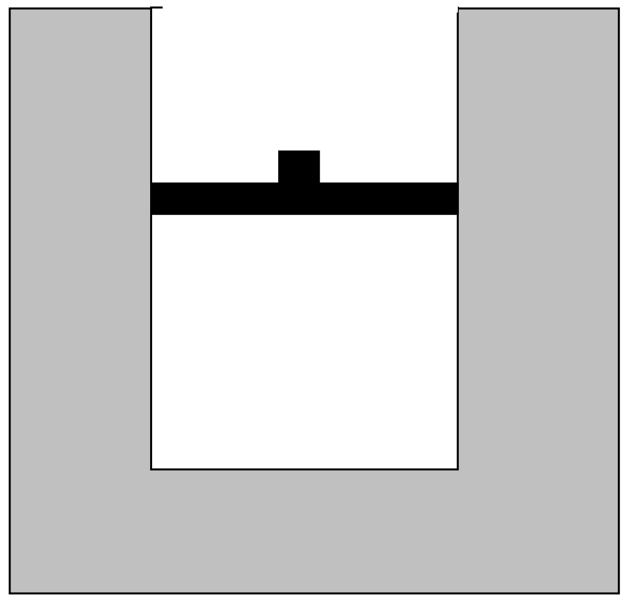
But first, have them draw a diagram…

- *Sketch a P-V diagram of Process #1 and label (with the appropriate letter) the states that occur at times A, B, C, and D.*

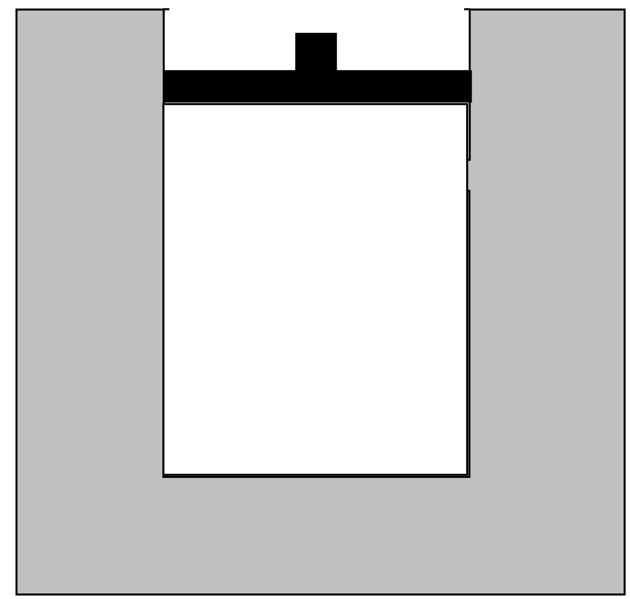


System heated

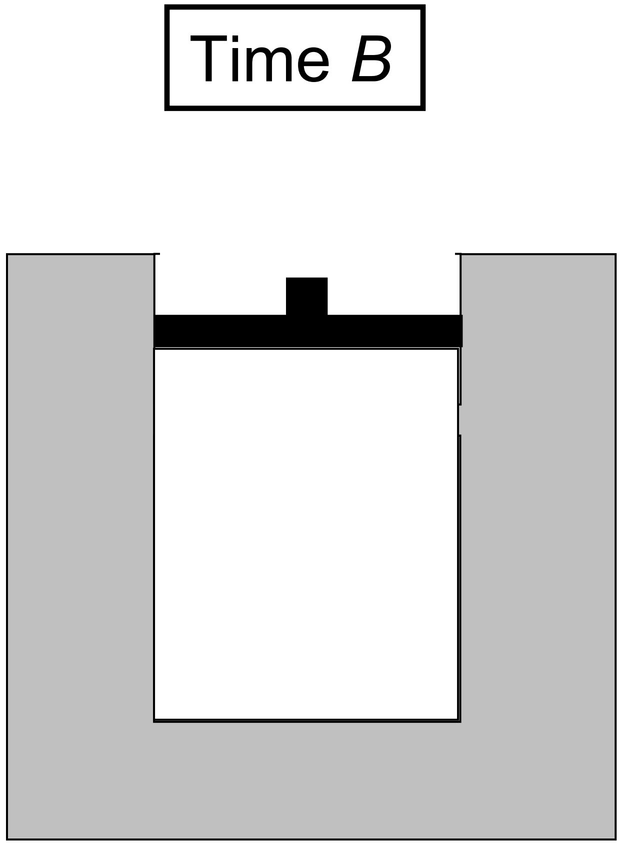
Time *A*



Time *B*

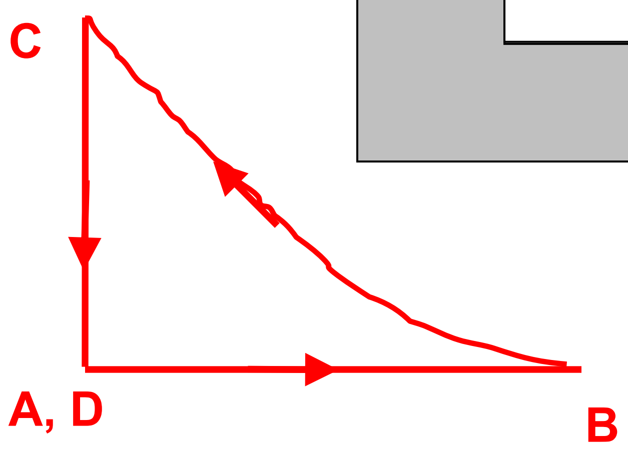


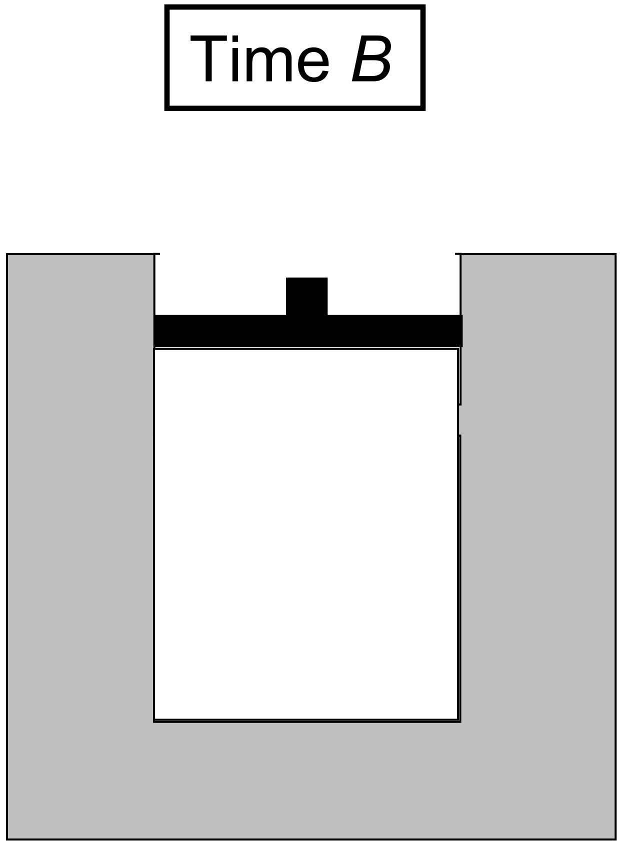
System heated, piston goes up.



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

Explain your answer.





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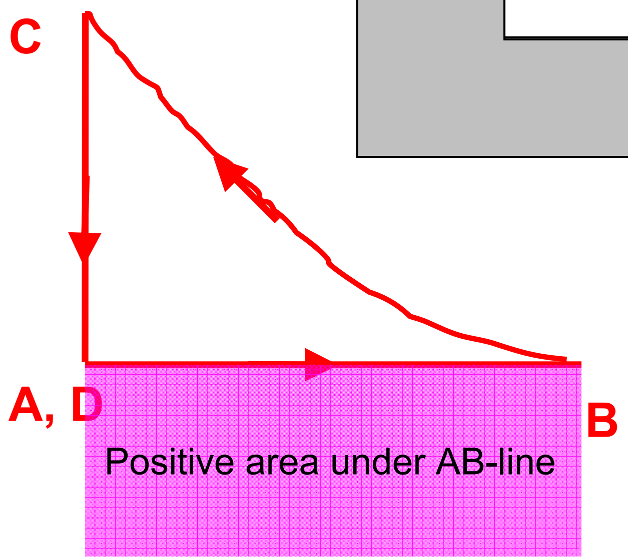

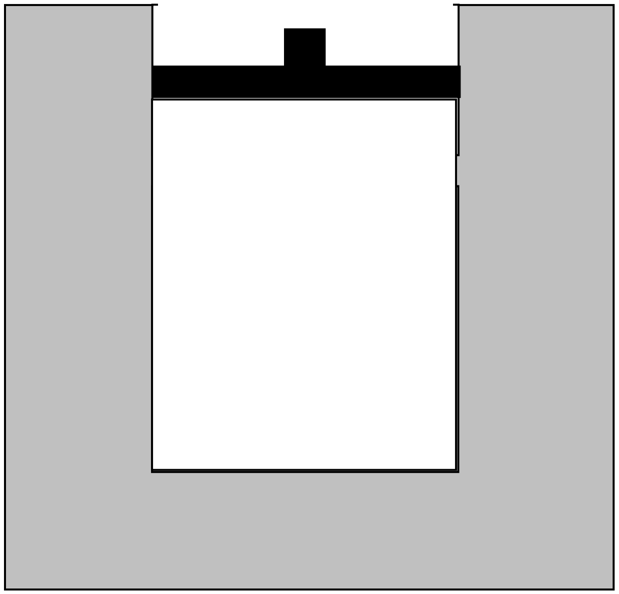

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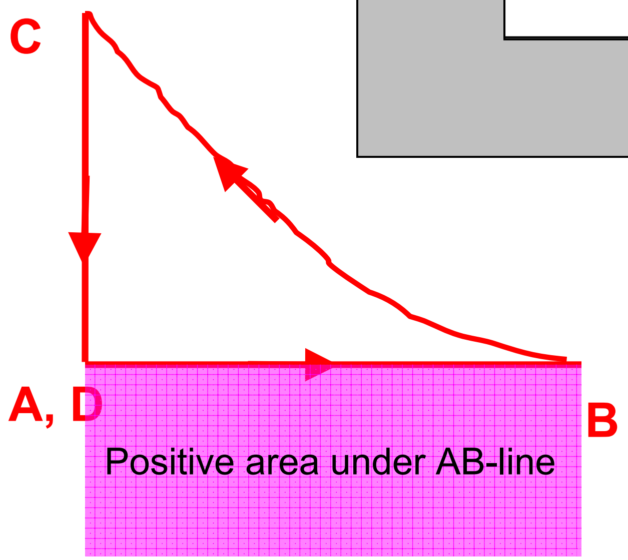
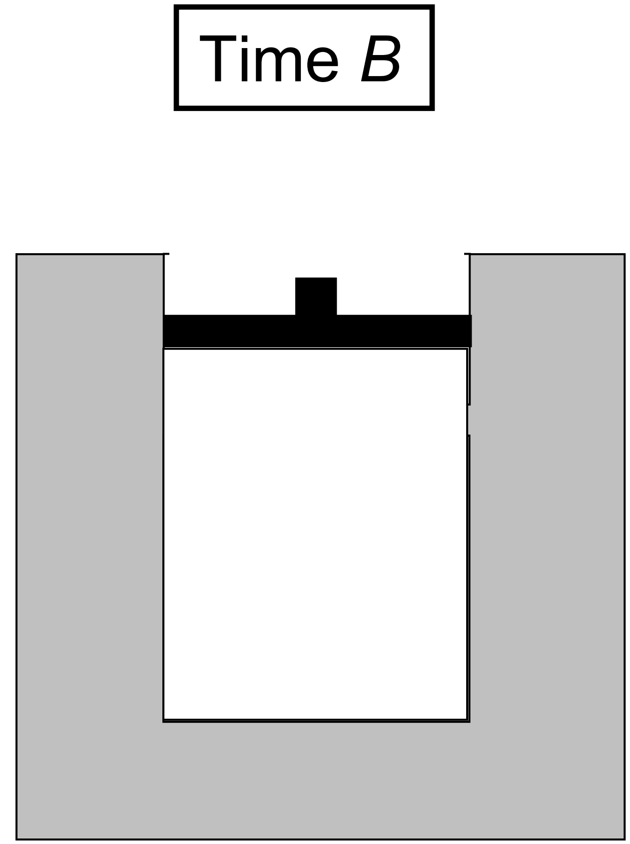
Explain your answer.



2) Is heat transferred *to* the system, *away* from the system, or is there *no heat transfer*?

Explain your answer.



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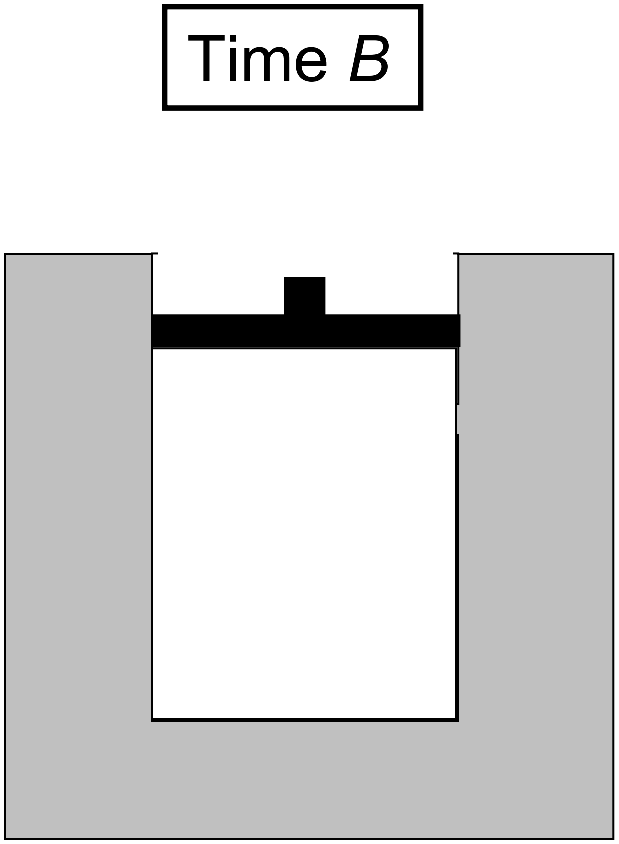
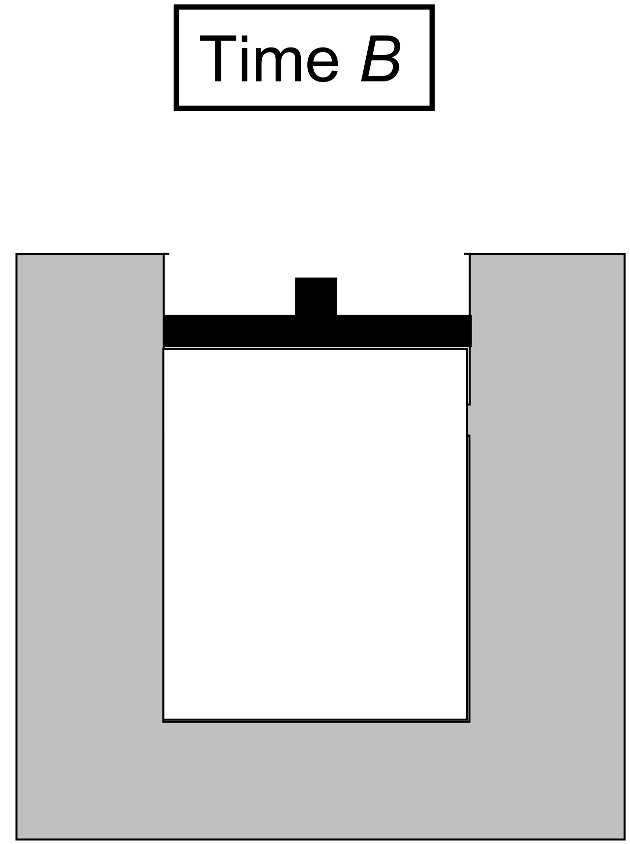
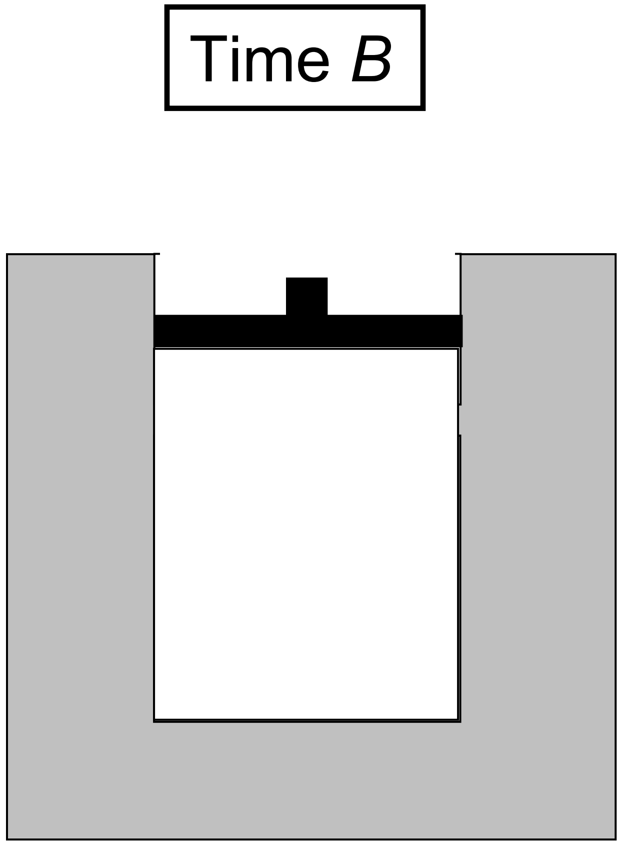


Problem stated: *"…the water container is gradually heated…"*

3) Does the internal energy *increase*, *decrease*, or *remain the same*?

Explain your answer.

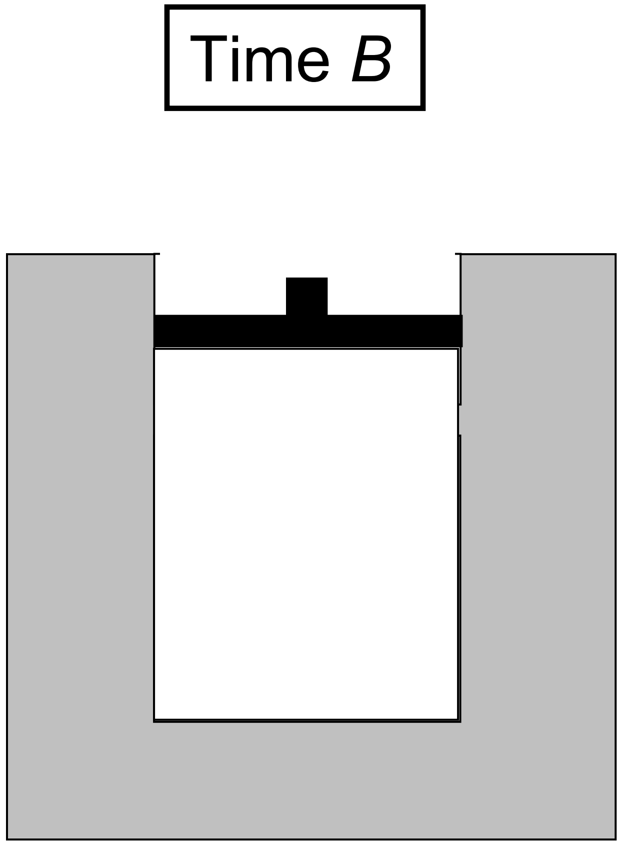




3) Does the internal energy *increase*, *decrease*, or *remain the same*?

Explain your answer.

Ideal Gas: *Pressure constant but volume increases →*



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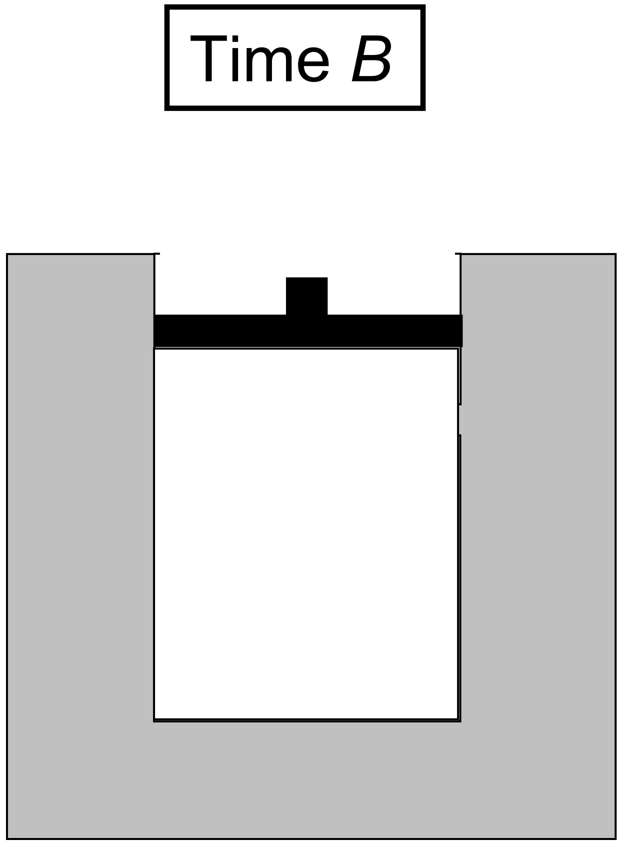
Explain your answer.

Ideal Gas: *Pressure constant but volume increases →*

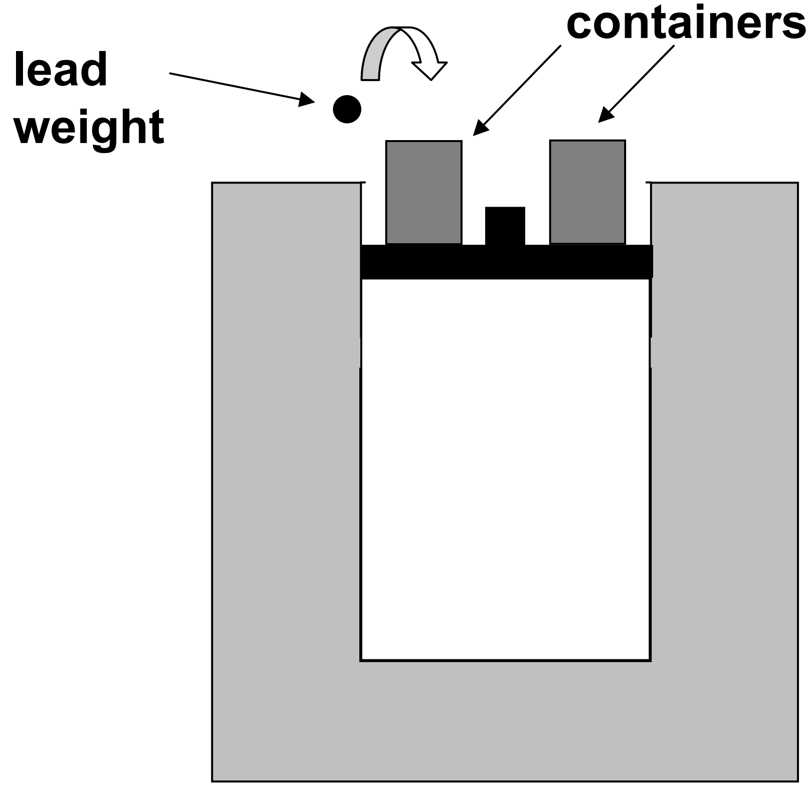


3) Does the internal energy *increase*, *decrease*, or *remain the same*?

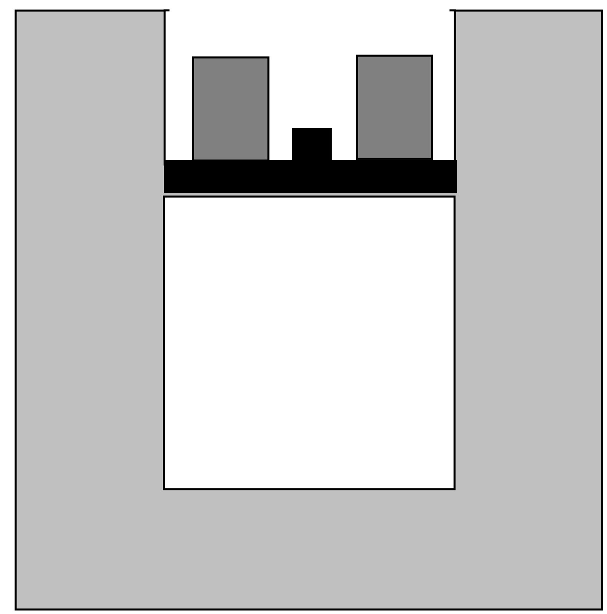
Explain your answer.

Ideal Gas: *Pressure constant but volume increases → temperature increases → internal energy increases*

Time *B*

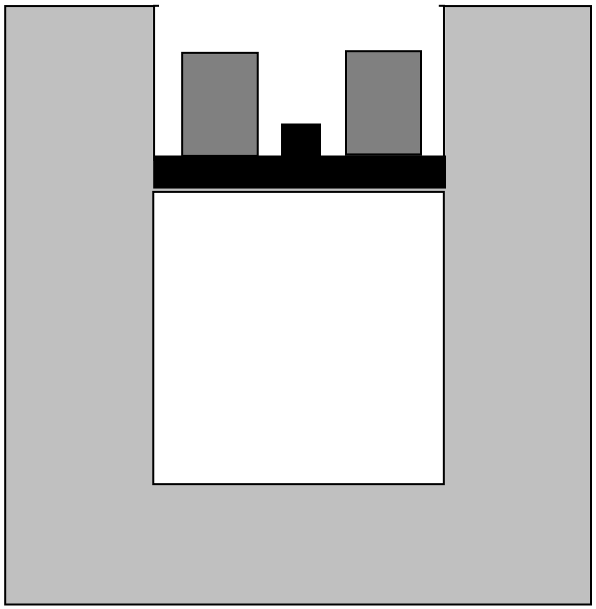


Time *C*

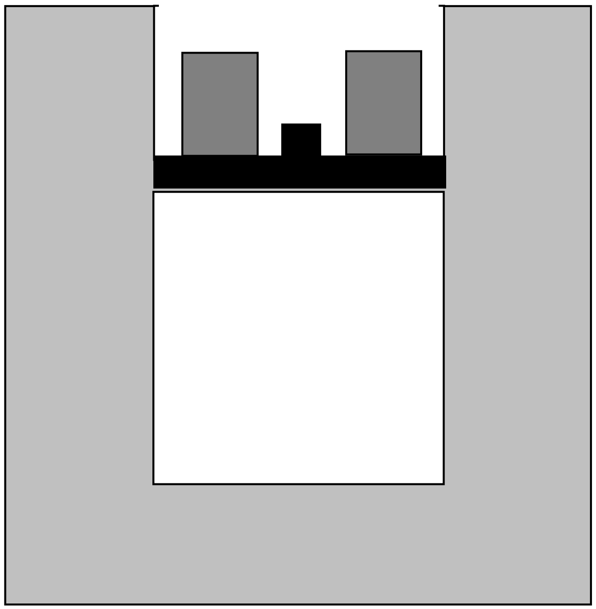


Time *C*

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



Time *C*

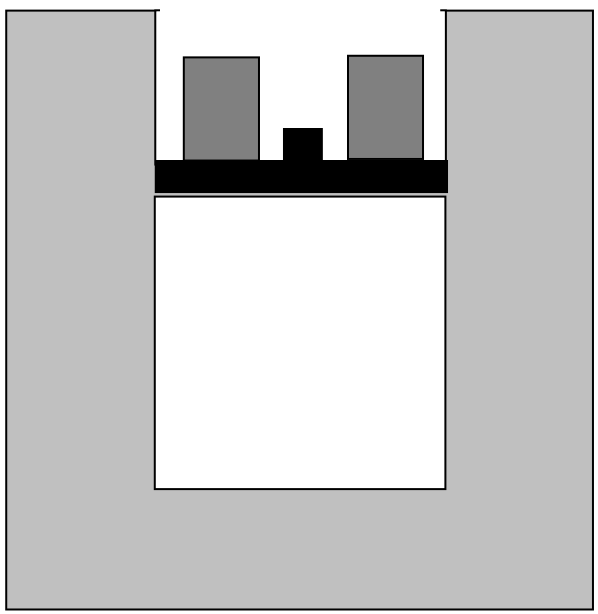


4) For the process B → C, is the work done by the system (W_{BC}) *positive*, *negative*, or *zero*?

Gas is compressed, so it does negative *work on piston*

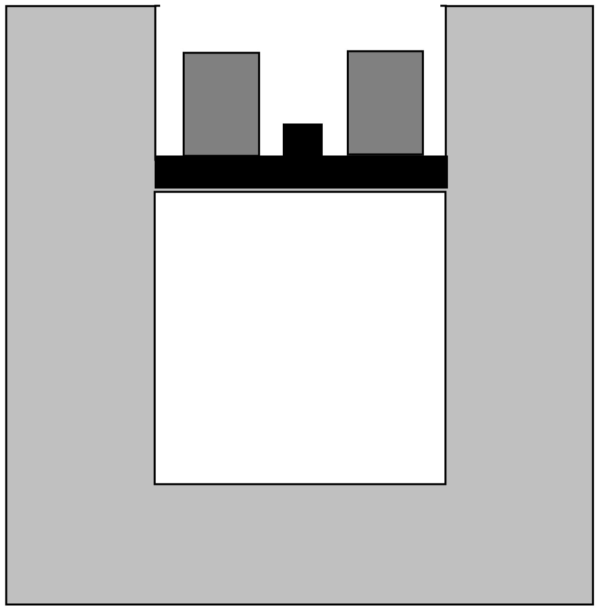
Time *C*

5) Does the internal energy *increase*, *decrease*, or *remain the same*?



Time *C*

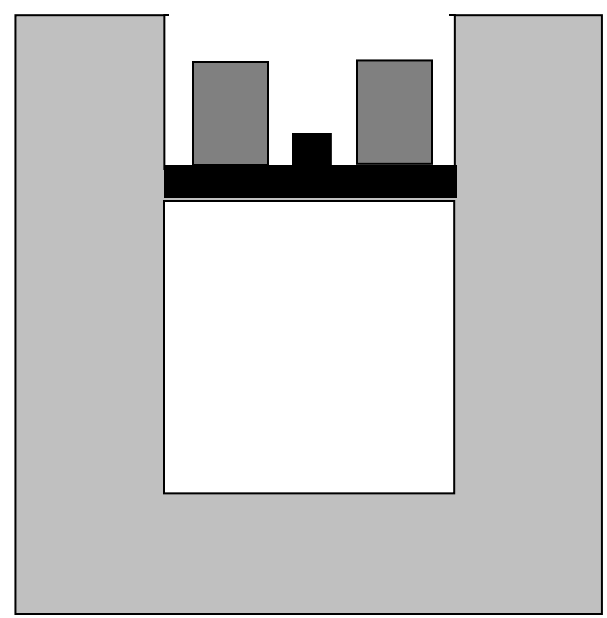
5) Does the internal energy *increase*, *decrease*, or *remain the same*?



Temperature does not change, so internal energy is constant.

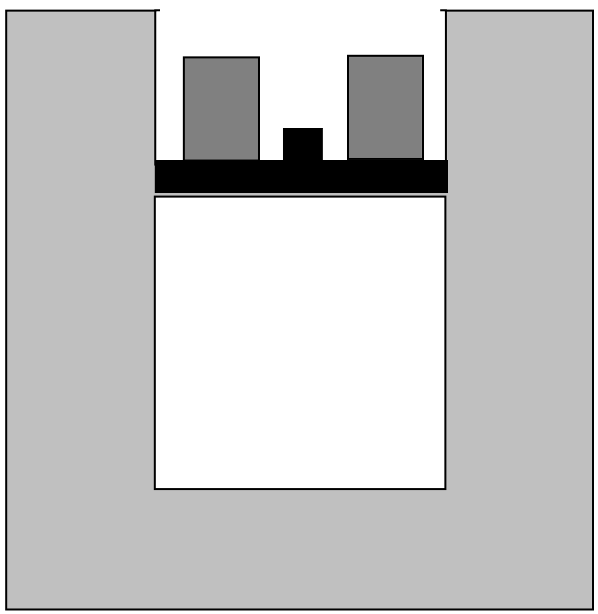
Time *C*

6) Is there heat transfer *from the gas to the water*, *from the water to the gas*, or is there *no heat transfer*? Explain.



Time *C*

6) Is there heat transfer *from the gas to the water*, *from the water to the gas*, or is there *no heat transfer*? Explain.

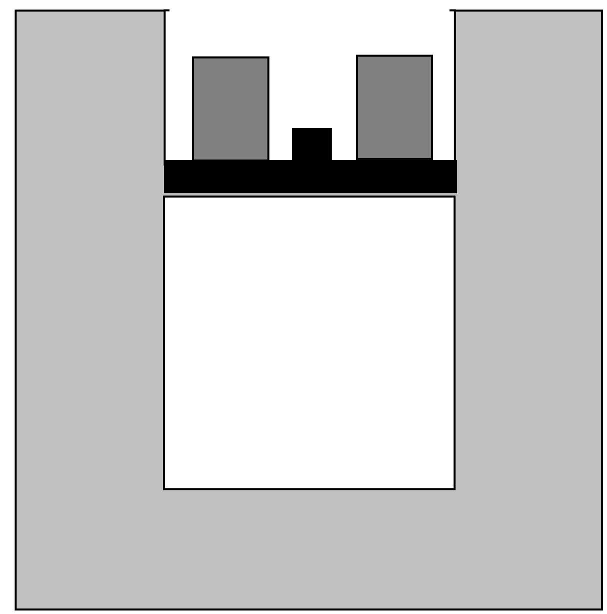


Energy transfer to *gas from piston, so must be energy transfer* out of *gas through heating.*

Time *C*

6) Is there heat transfer *from the gas to the water*, *from the water to the gas*, or is there *no heat transfer*? Explain.

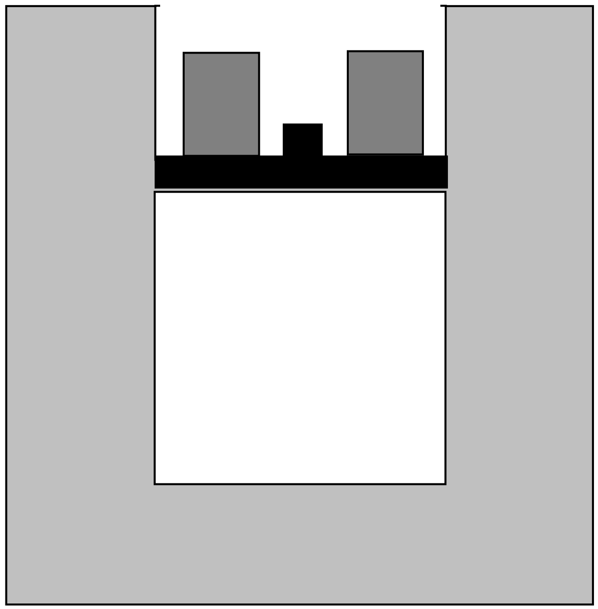
Does the temperature of the water change during this process? Explain why or why not.



Time *C*

6) Is there heat transfer *from the gas to the water*, *from the water to the gas*, or is there *no heat transfer*? Explain.

Does the temperature of the water change during this process? Explain why or why not. *[No; it's a thermal reservoir]*



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.

5) For the process A → B, is the change in internal energy (ΔU_{AB}) *positive*, *negative*, or *zero*?

6) For the process B → C, is the change in internal energy (ΔU_{BC}) *positive*, *negative*, or *zero*?

7) For the process C → D, is the change in internal energy (ΔU_{CD}) *positive*, *negative*, or *zero*?

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

largest $|\Delta U_{AB}| = |\Delta U_{CD}| > |\Delta U_{BC}| = 0$ *smallest*

Explain your reasoning.

Worksheet Strategy

- First, allow students to read description of entire process and answer questions regarding work and heat.
- Then, prompt students for step-by-step responses.
- Finally, compare results with answers given to original question.

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*?

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.

Entropy and Second-Law Questions

- Heat-engine questions
- Questions about entropy increase

Entropy and Second-Law Questions

- Heat-engine questions
- Questions about entropy increase

Heat Engines and Second-Law Issues

- After extensive study and review of first law of thermodynamics, cyclic processes, Carnot heat engines, efficiencies, etc., students were given pretest regarding various possible (or impossible) versions of two-temperature heat engines.

Heat-engines and Second-Law Issues

- Most advanced students are initially able to recognize that “perfect heat engines” (i.e., 100% conversion of heat into work) violate second law;
- Most are initially *unable* to recognize that engines with greater than ideal (“Carnot”) efficiency also violate second law (consistent with result of Cochran and Heron, 2006);
- After (special) instruction, most students recognize impossibility of super-efficient engines, but still have difficulties understanding cyclic-process requirement of $\Delta S = 0$; many also still confused about $\Delta U = 0$.

Entropy and Second-Law Questions

- Heat-engine questions
- Questions about entropy increase

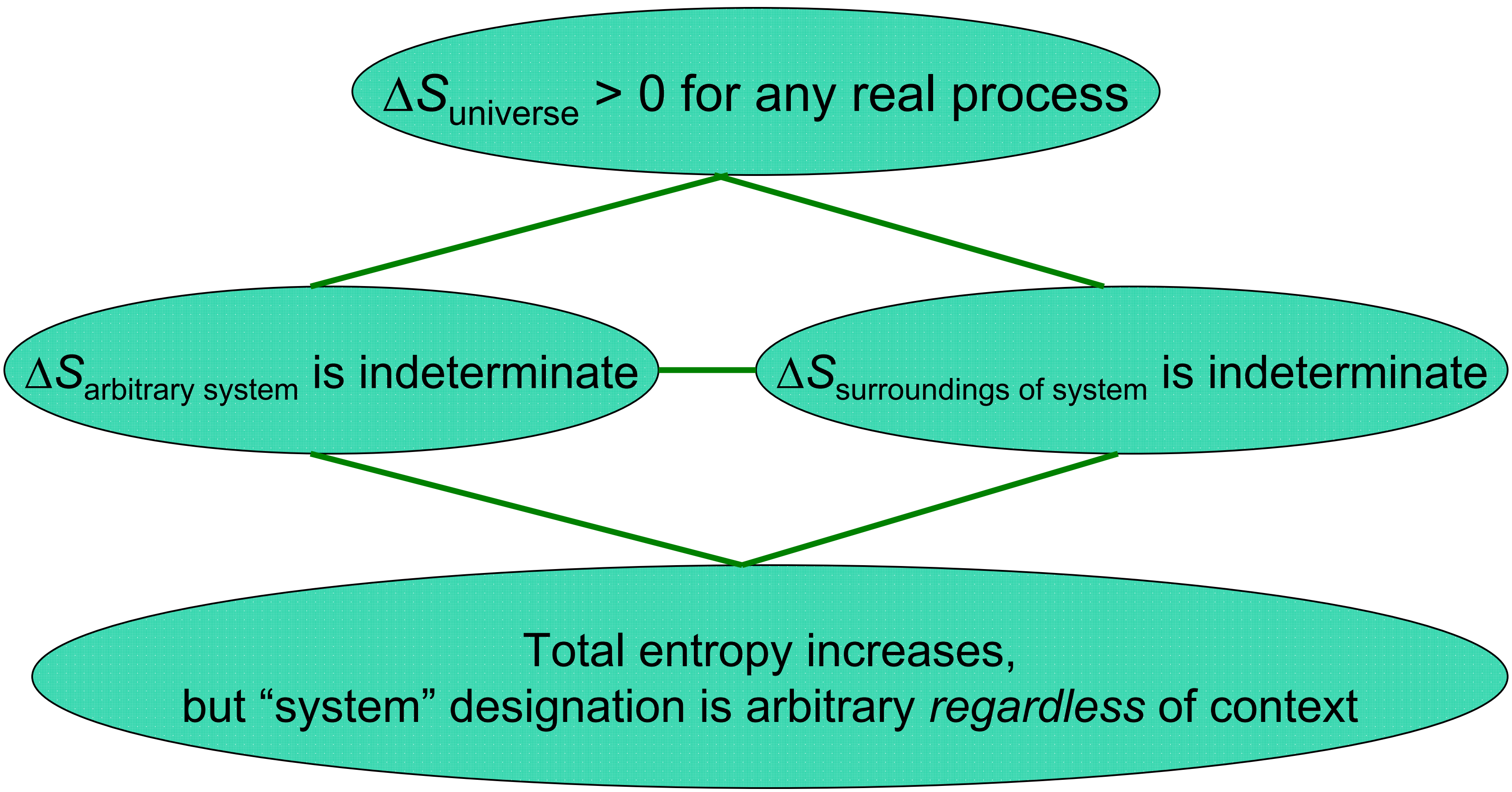
Entropy and Second-Law Questions

- Heat-engine questions
- Questions about entropy increase

Entropy and Second-Law Questions

- Heat-engine questions
- Questions about entropy increase:
  - “General-context” and “Concrete-context” questions

Entropy-Increase Target Concepts



General-Context Question

[Introductory-Course Version]

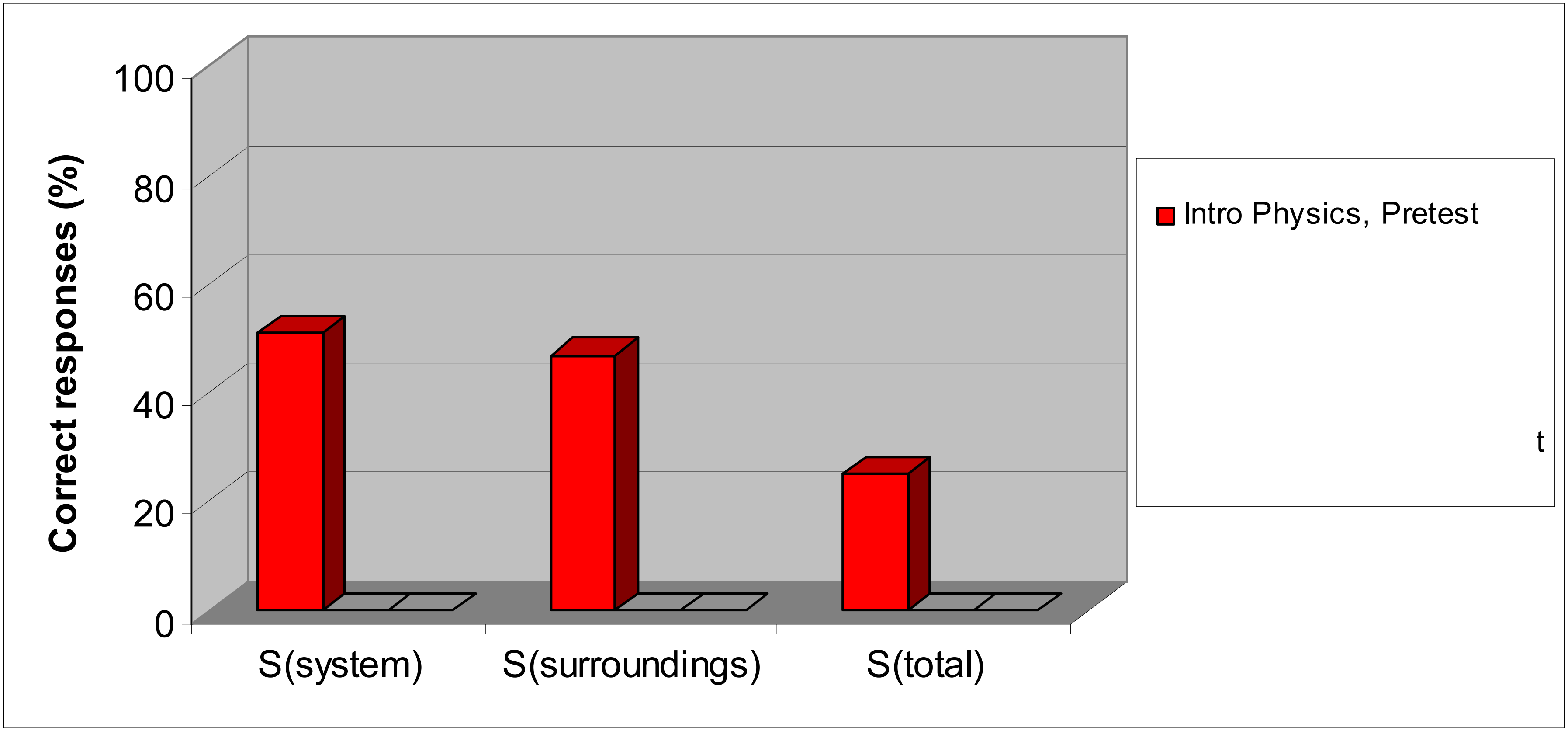
For each of the following questions consider a system undergoing a naturally occurring ("spontaneous") process. The system can exchange energy with its surroundings.

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 General-Context Questions



Less than 52% correct on each question on pretest

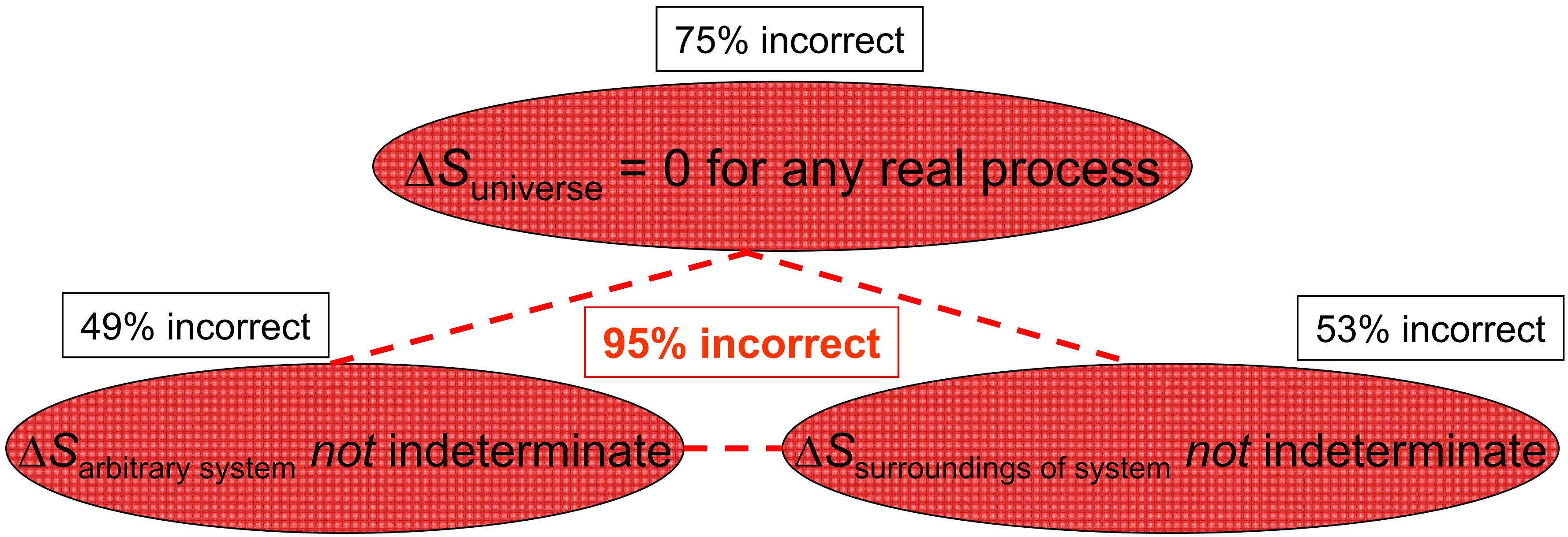
Introductory Physics Students' Thinking on Spontaneous Processes

- 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-Increase Target Concepts

$\Delta S_{universe} > 0$ for any real process

Students' Ideas, Pre-Instruction



"Concrete-Context" Question

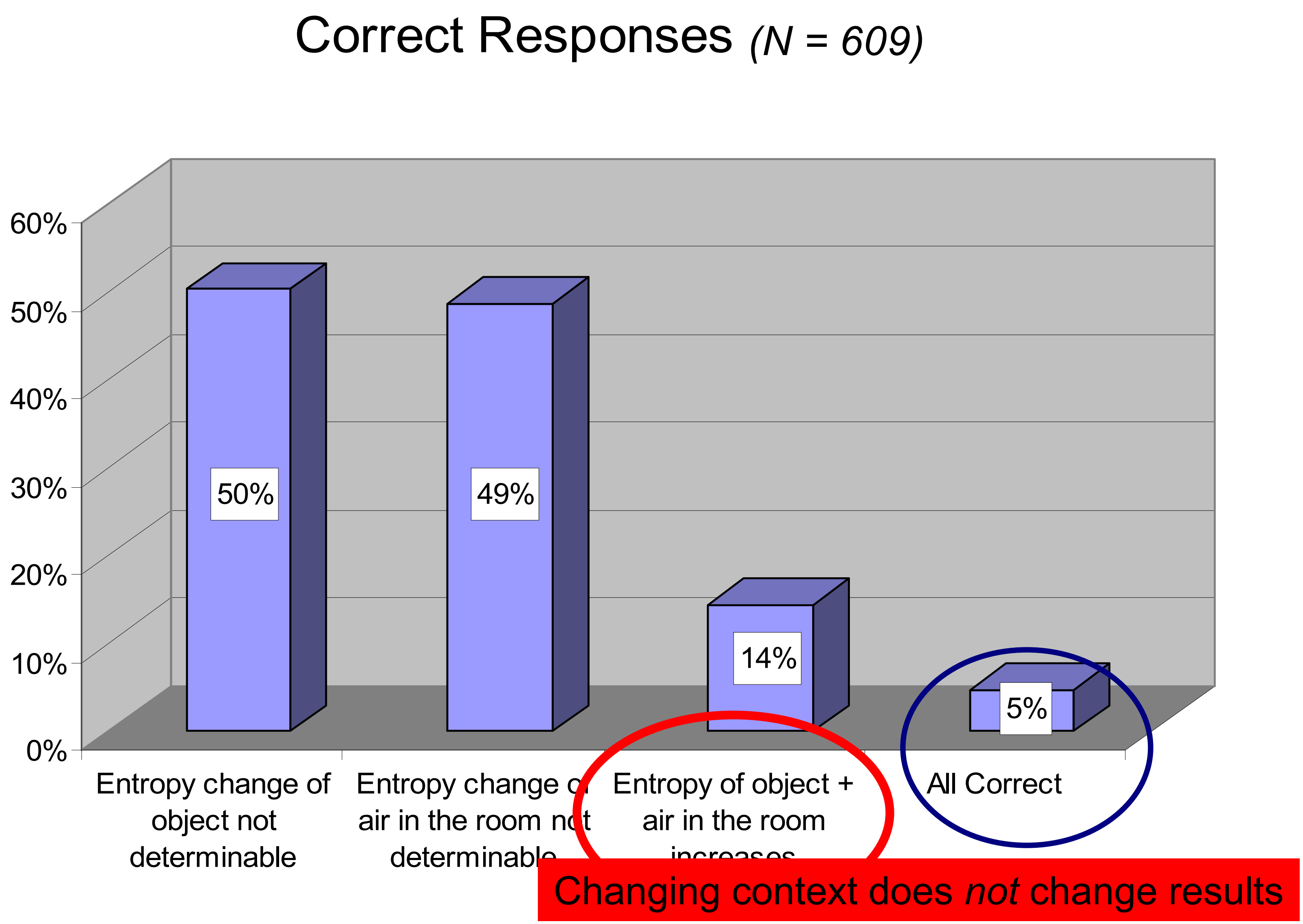
An object is placed in a thermally insulated room that contains air. The object and the air in the room are initially at different temperatures. The object and the air in the room are allowed to exchange energy with each other, but the air in the room does not exchange energy with the rest of the world or with the insulating walls.

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

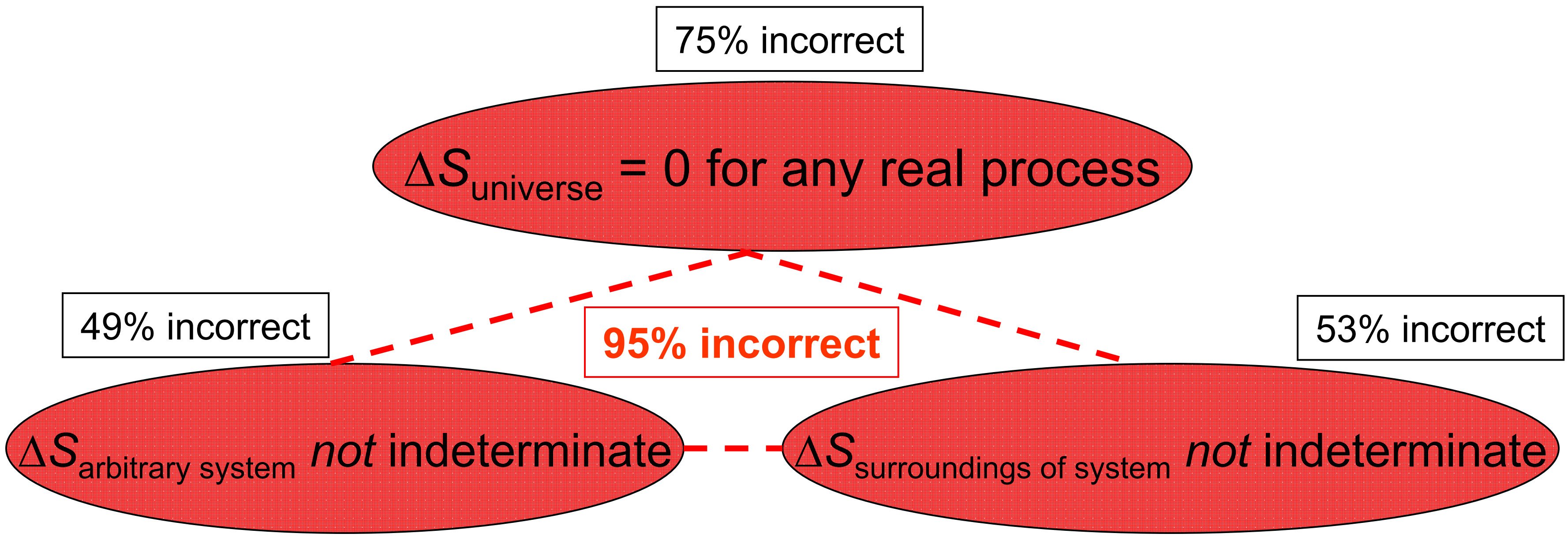
B. During this process, does the entropy of the **air in the room** [S_{air}] *increase*, *decrease*, *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

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

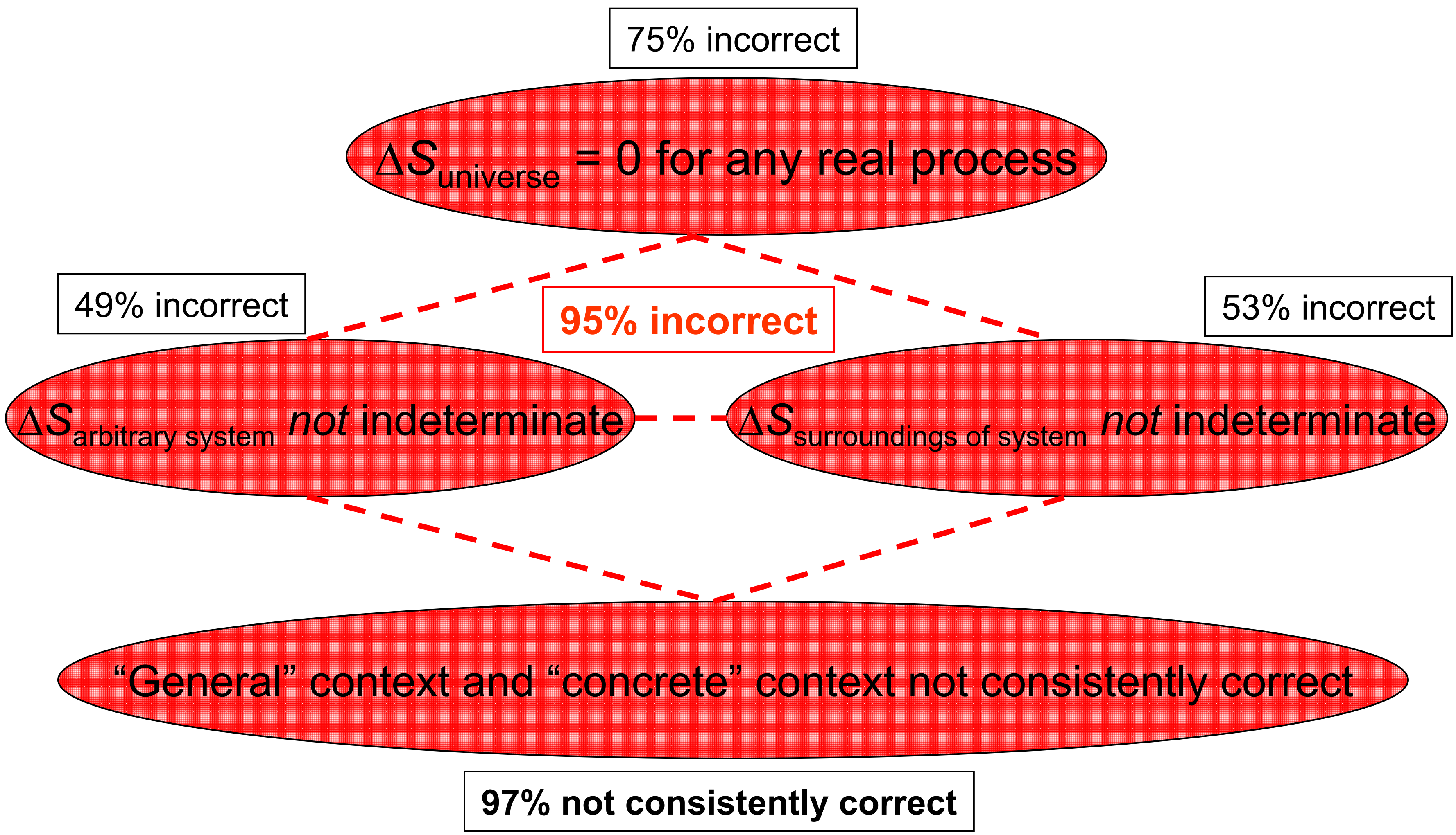
Responses to Concrete-Context Questions



Students' Ideas, Pre-Instruction



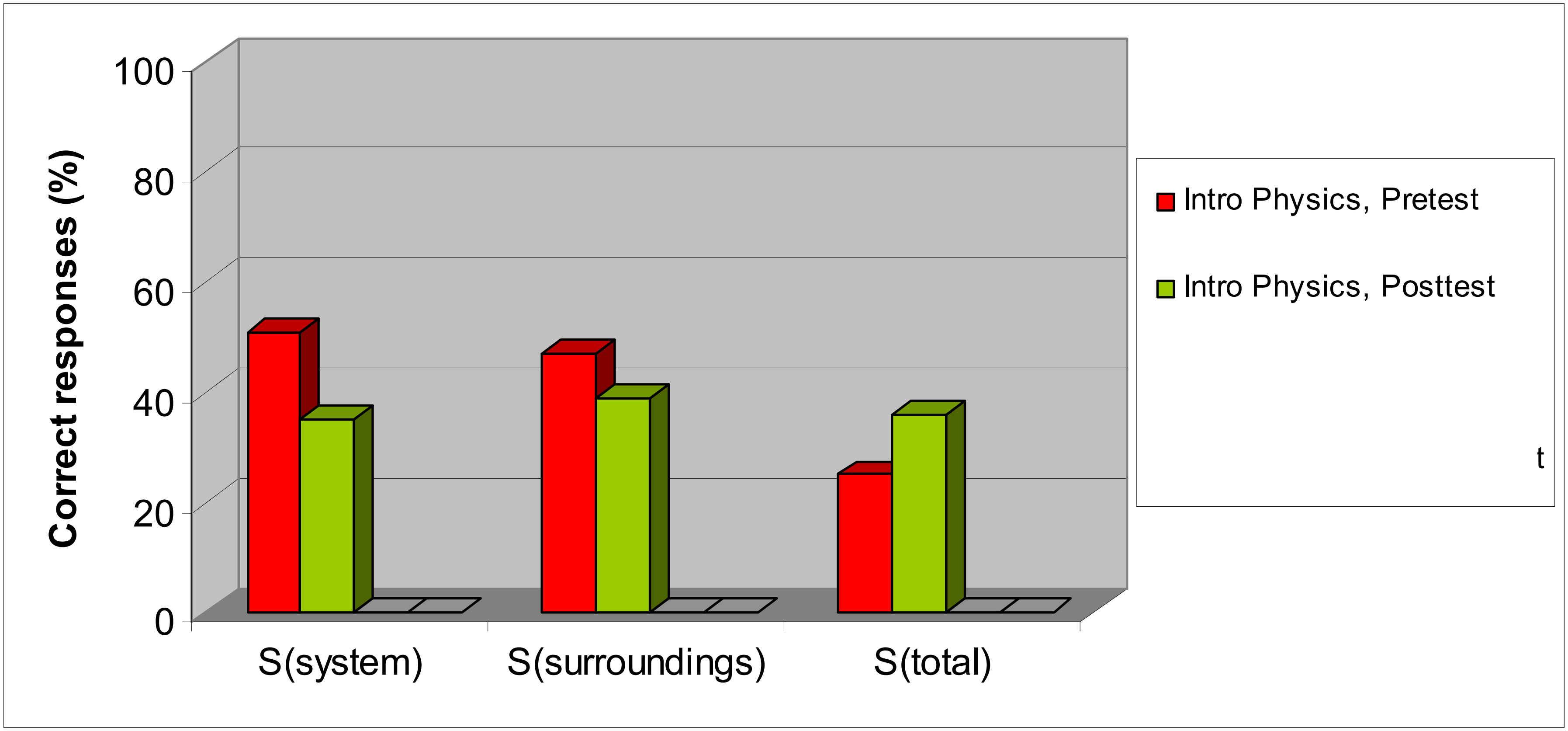
Students' Ideas, Pre-Instruction



How does student thinking change *after* instruction?

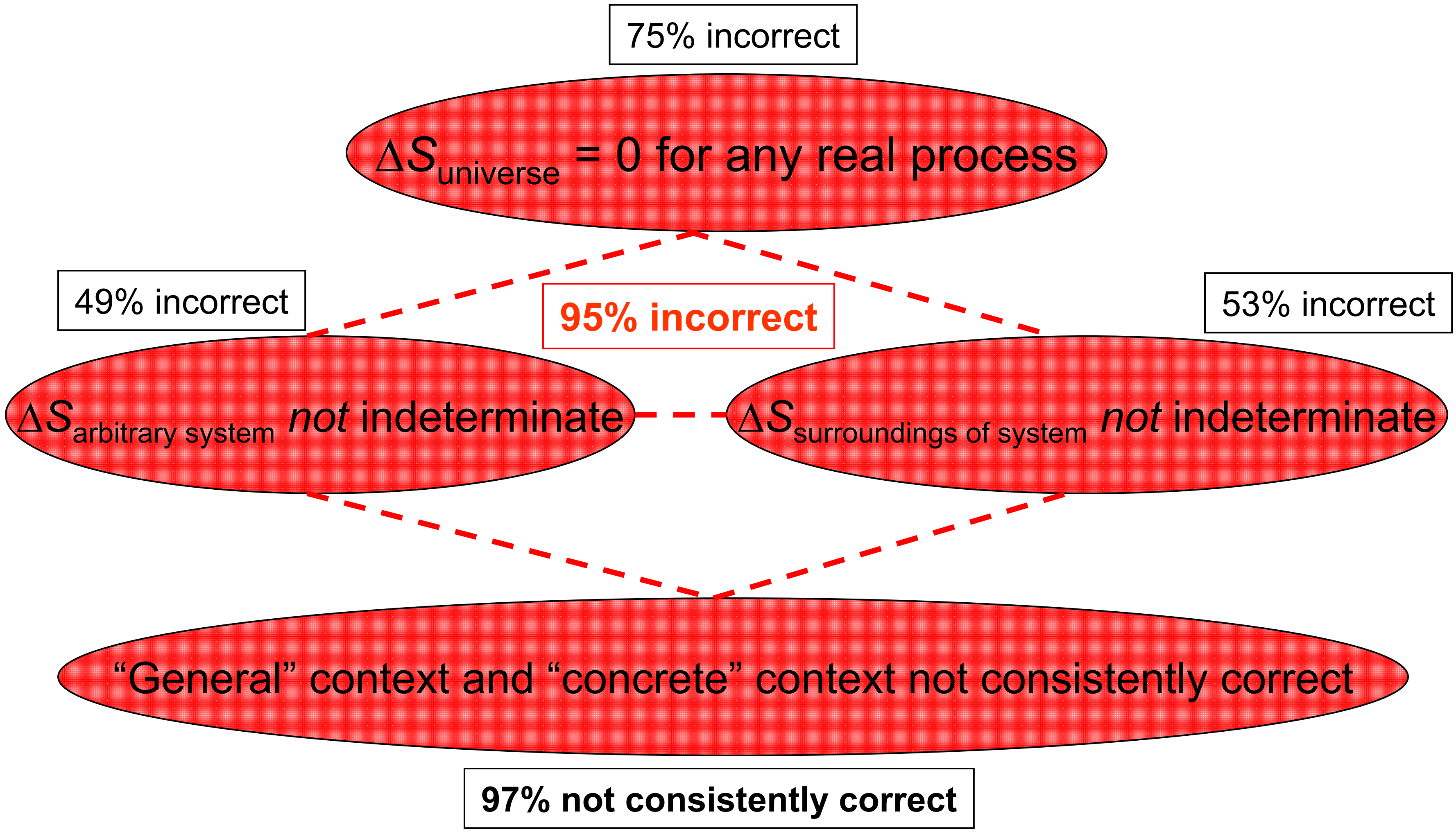
Responses to General-Context Questions

before … and *after* instruction…



Little change on post-test

Students' Ideas, Pre-Instruction



Students' Ideas, Pre-Instruction

75% incorrect

$\Delta S_{universe} = 0$ for any real process

Students' Ideas, Post-Instruction

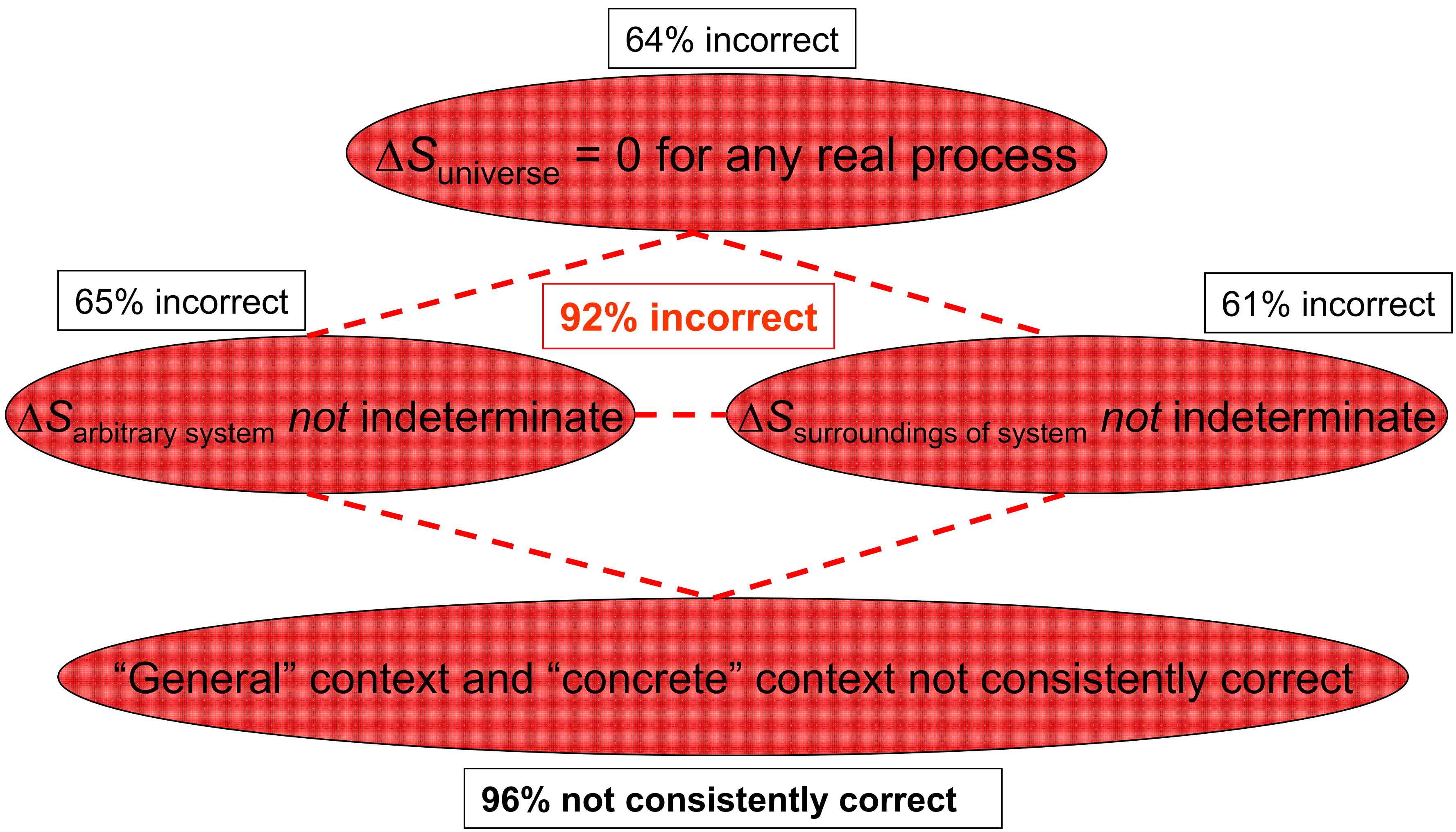
[no special instruction]

64% incorrect

$\Delta S_{universe}$ = 0 for any real process

Students' Ideas, Post-Instruction

[no special instruction]



“Total entropy” responses

- Nearly two-thirds of all students responded that the “total entropy” (“system plus surroundings” or “object plus air”) remains the same.
- We can further categorize these responses according to the ways in which the other two parts were answered
- 90% of these responses fall into one of two specific conservation arguments:

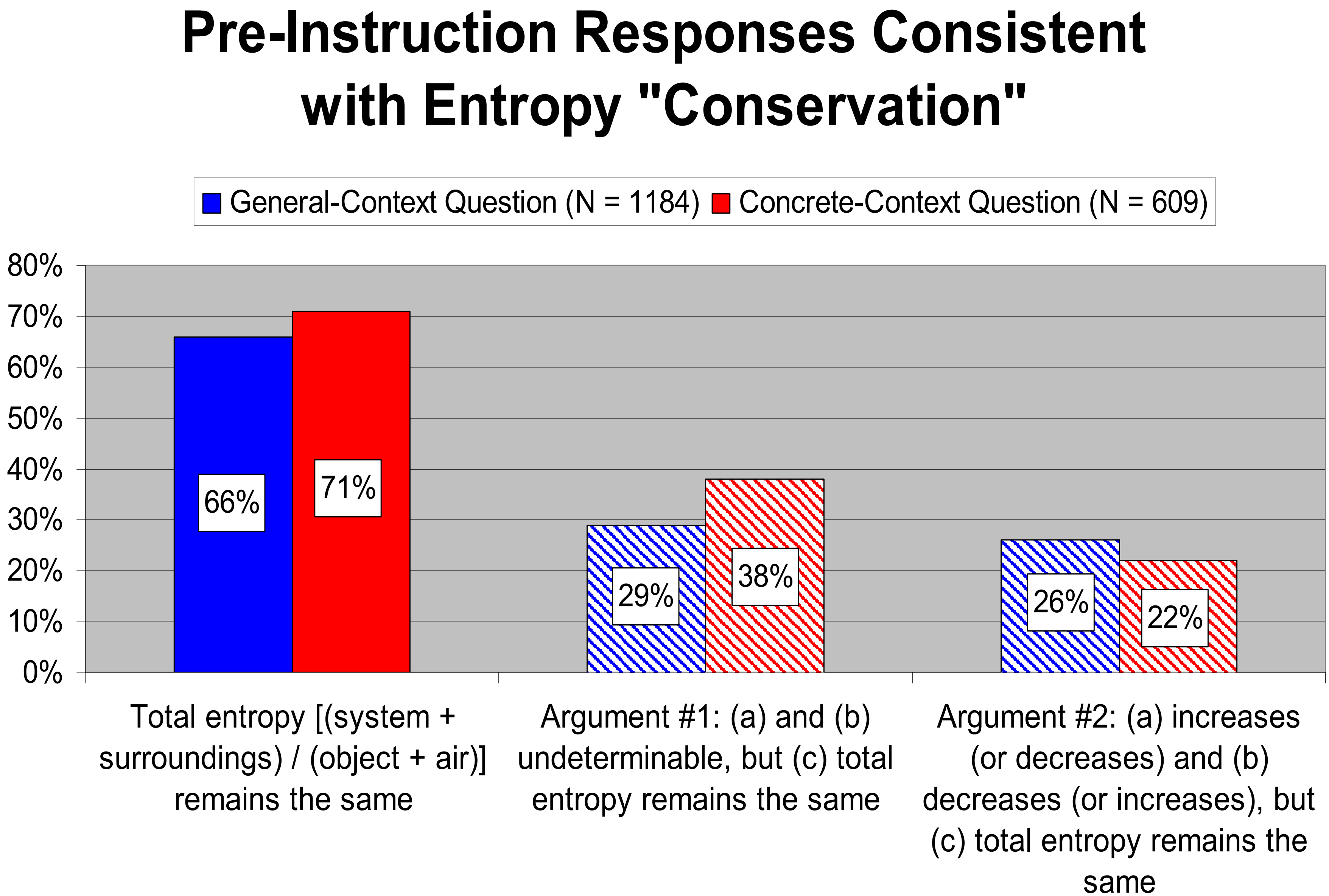
Conservation Arguments

Conservation Argument #1

ΔS_{System} not determinable,
$\Delta S_{\text{Surroundings}}$ not determinable, and
$S_{\text{System}} + S_{\text{Surroundings}}$ stays the same

Conservation Argument #2

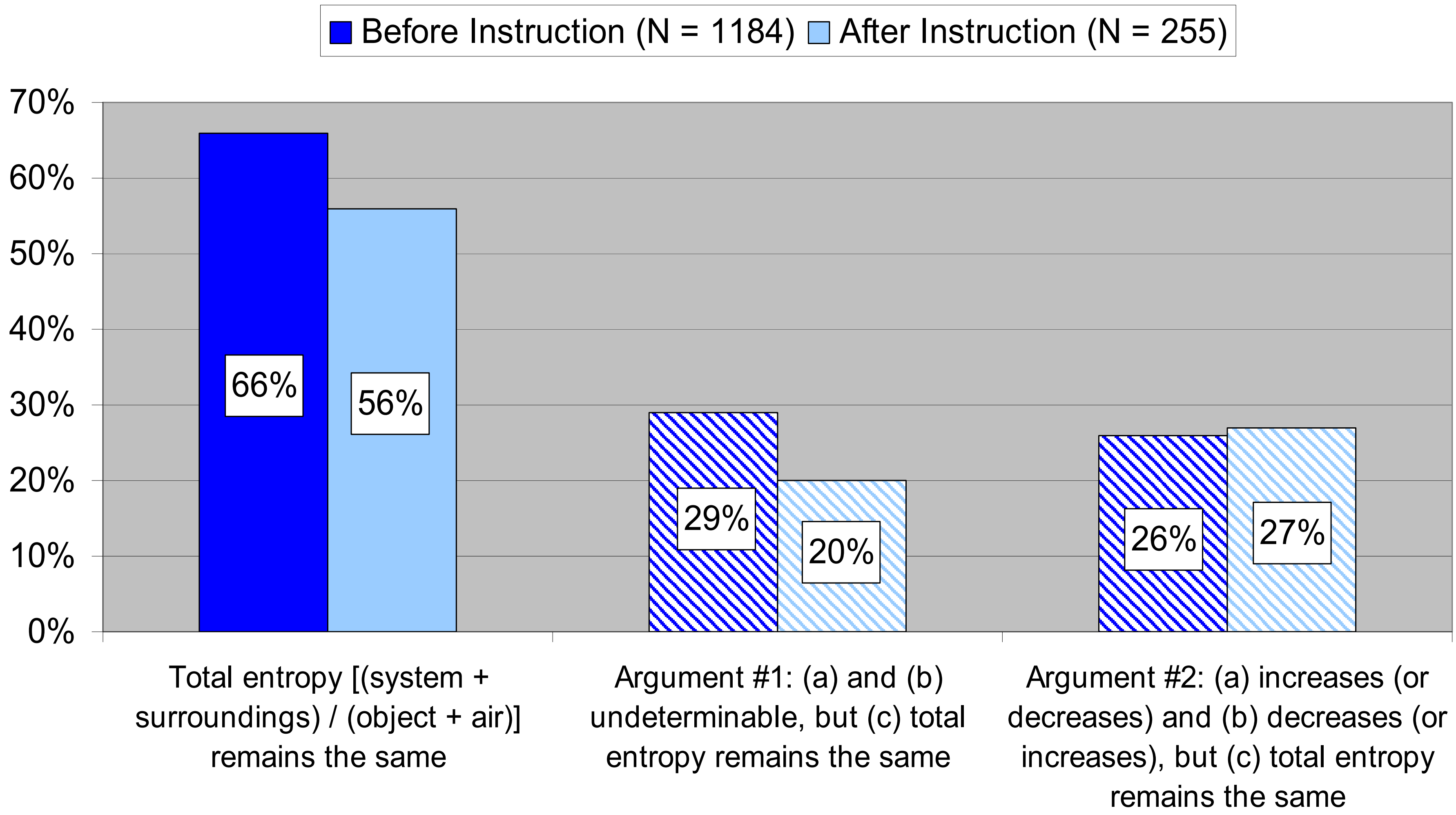
S_{System} increases [*decreases*],
$S_{\text{Surroundings}}$ decreases [*increases*], and
$S_{\text{System}} + S_{\text{Surroundings}}$ stays the same

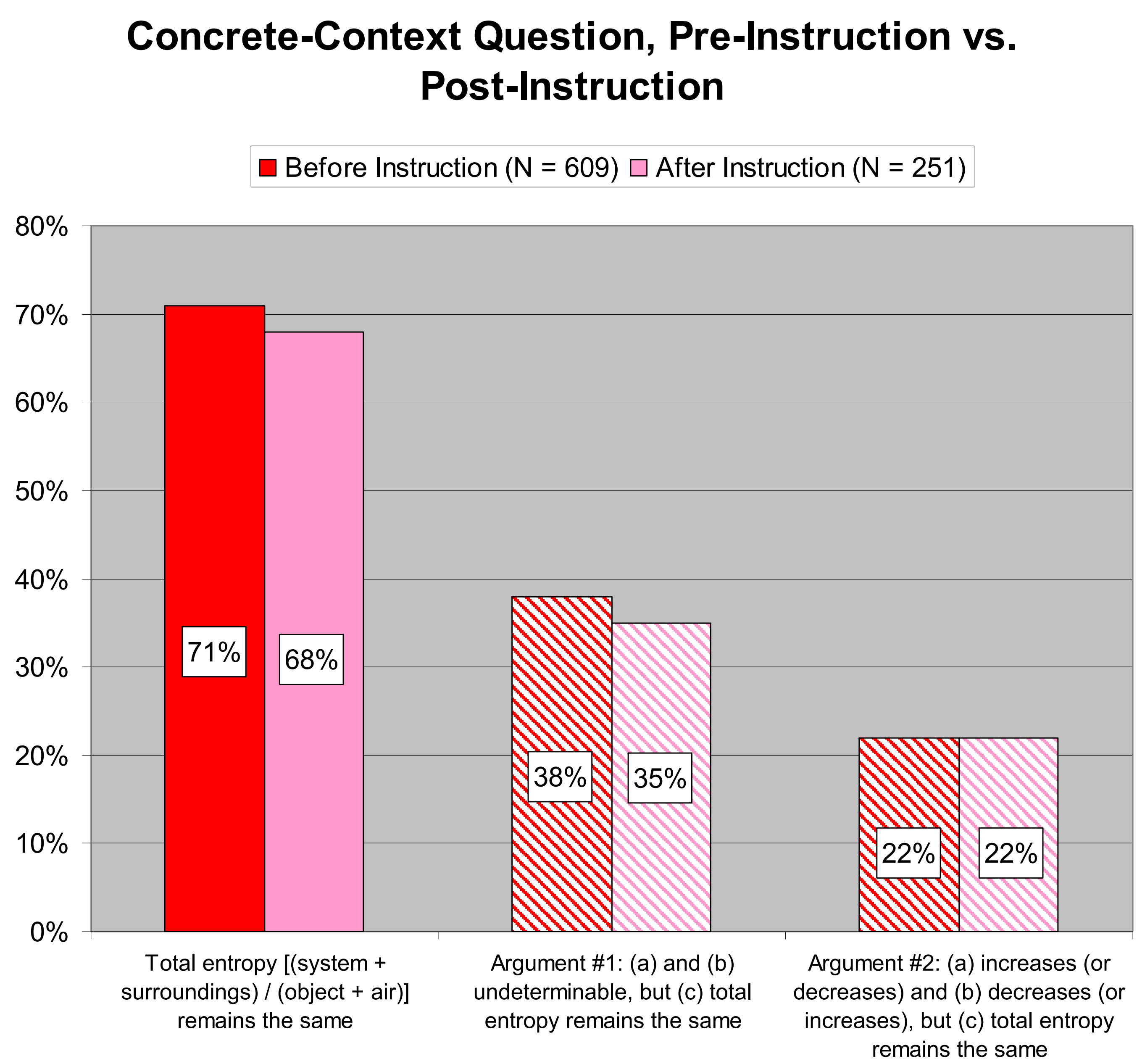

Pre-Instruction Responses Consistent with Entropy "Conservation"
General-Context Question (N = 1184)
Concrete-Context Question (N = 609)
80%
70%
60%
50%
40%
30%
20%
10%
0%
66%
71%
29%
38%
26%
22%
Total entropy [(system + surroundings) / (object + air)] remains the same
Argument #1: (a) and (b) undeterminable, but (c) total entropy remains the same
Argument #2: (a) increases (or decreases) and (b) decreases (or increases), but (c) total entropy remains the same

Pre- vs. Post-instruction

- Post-instruction testing occurred after all instruction on thermodynamics was complete

General-Context Question Pre-Instruction vs. Post-Instruction




Concrete-Context Question, Pre-Instruction vs. Post-Instruction
Before Instruction (N = 609)
After Instruction (N = 251)
80%
70%
60%
50%
40%
30%
20%
10%
0%
71%
68%
38%
35%
22%
22%
Total entropy [(system + surroundings) / (object + air)] remains the same
Argument #1: (a) and (b) undeterminable, but (c) total entropy remains the same
Argument #2: (a) increases (or decreases) and (b) decreases (or increases), but (c) total entropy remains the same

Findings from Entropy Questions

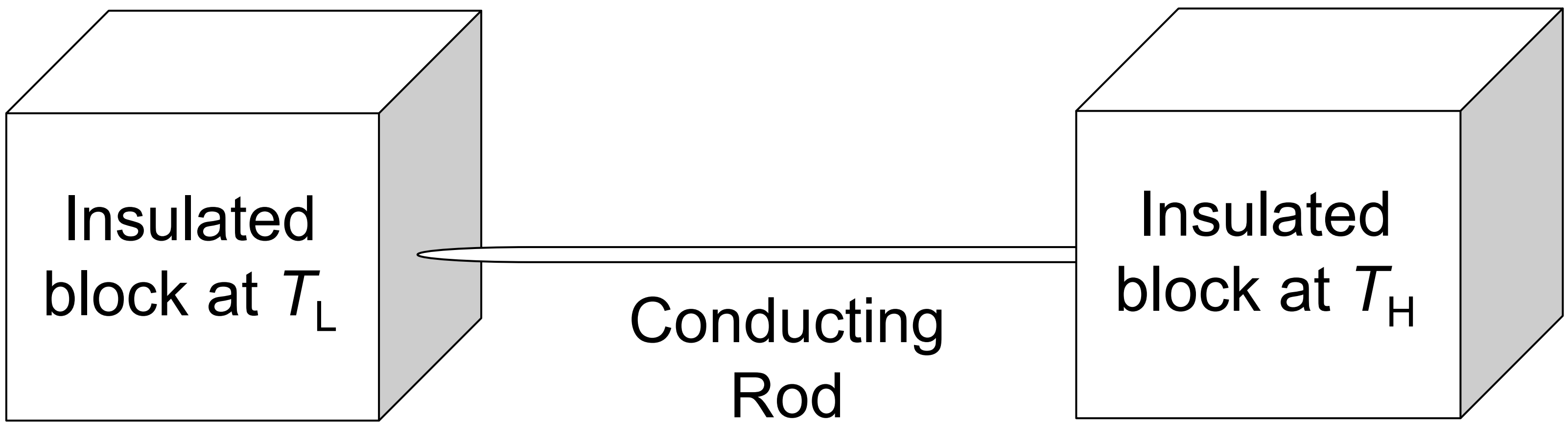
Both before and after instruction…

In both a general and a concrete context:

- Introductory students have significant difficulty applying fundamental concepts of entropy
- More than half of all students utilized inappropriate conservation arguments in the context of entropy

"Two-Blocks" Entropy Tutorial

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



- Consider slow heat transfer process between two thermal reservoirs (insulated metal block connected by thin metal pipe)
  - Does total energy change during process? *[No]*
  - Does total entropy change during process? *[Yes]*

2. During the heat transfer process, consider ΔS_H and ΔS_L, the change in entropy of the high-temperature block and low-temperature block, respectively.

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b) Is ΔS_L, the change in entropy of the low-temperature block, *positive*, *negative*, or *zero*?

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b) Is ΔS_{L}, the change in entropy of the low-temperature block, *positive*, *negative*, or *zero*?

Positive. $\Delta S_L = \dfrac{Q_L}{T_L}$ ***Heat transfer to the low-temperature block is positive, and temperature is positive.***

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Does this mean the entropy of the low-temperature block *increases*, *decreases*, or *remains the same*?

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Increases, since the final value is greater than the initial value.

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c) Consider the magnitudes (absolute values) of ΔS_H and ΔS_L. Is the absolute value of one larger than the other? If so, which one? Explain.

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c) Consider the magnitudes (absolute values) of ΔS_H and ΔS_L. Is the absolute value of one larger than the other? If so, which one? Explain.

$\Delta S_H = \frac{Q_H}{T_H}$ $\Delta S_L = \frac{Q_L}{T_L}$ ***; The heat transfers are equal in magnitude but T_L is less than T_H. Thus $|\Delta S_H|$ is less than $|\Delta S_L|$***

d) If we consider the actual values, is the sum [$\Delta S_H + \Delta S_L$] *positive*, *negative*, or *zero*?

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e) For this process, is entropy a conserved quantity? Justify your answer. Explain any differences between this answer and your answer to 1(e) above.

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e) For this process, is entropy a conserved quantity? Justify your answer. Explain any differences between this answer and your answer to 1(e) above.

No, there is more entropy after the process than before it started.

Fictional "Student Discussion" for Analysis…

You overhear a group of students discussing the above problem. Carefully read what each student is saying.

Student A: Well, the second law says that the entropy of the system is always increasing. Entropy always increases no matter what.

Student B: But how do you know which one is the system? Couldn't we just pick whatever we want to be the system and count everything else as the surroundings?

Student C: I don't think it matters which we call the system or the surroundings, and because of that we can't say that the system always increases. The second law states that the entropy of the system plus the surroundings will always increase.

Analyze each statement and discuss with your group the extent to which it is correct or incorrect. How do the students' ideas compare with your own discussion [about the insulated blocks] *on the previous page?*

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

Entropy Tutorial

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

- Guide students to find that:

> Entropy gain of low-temperature block is *larger* than entropy loss of high-temperature block, so *total entropy increases*

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

Entropy Tutorial

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

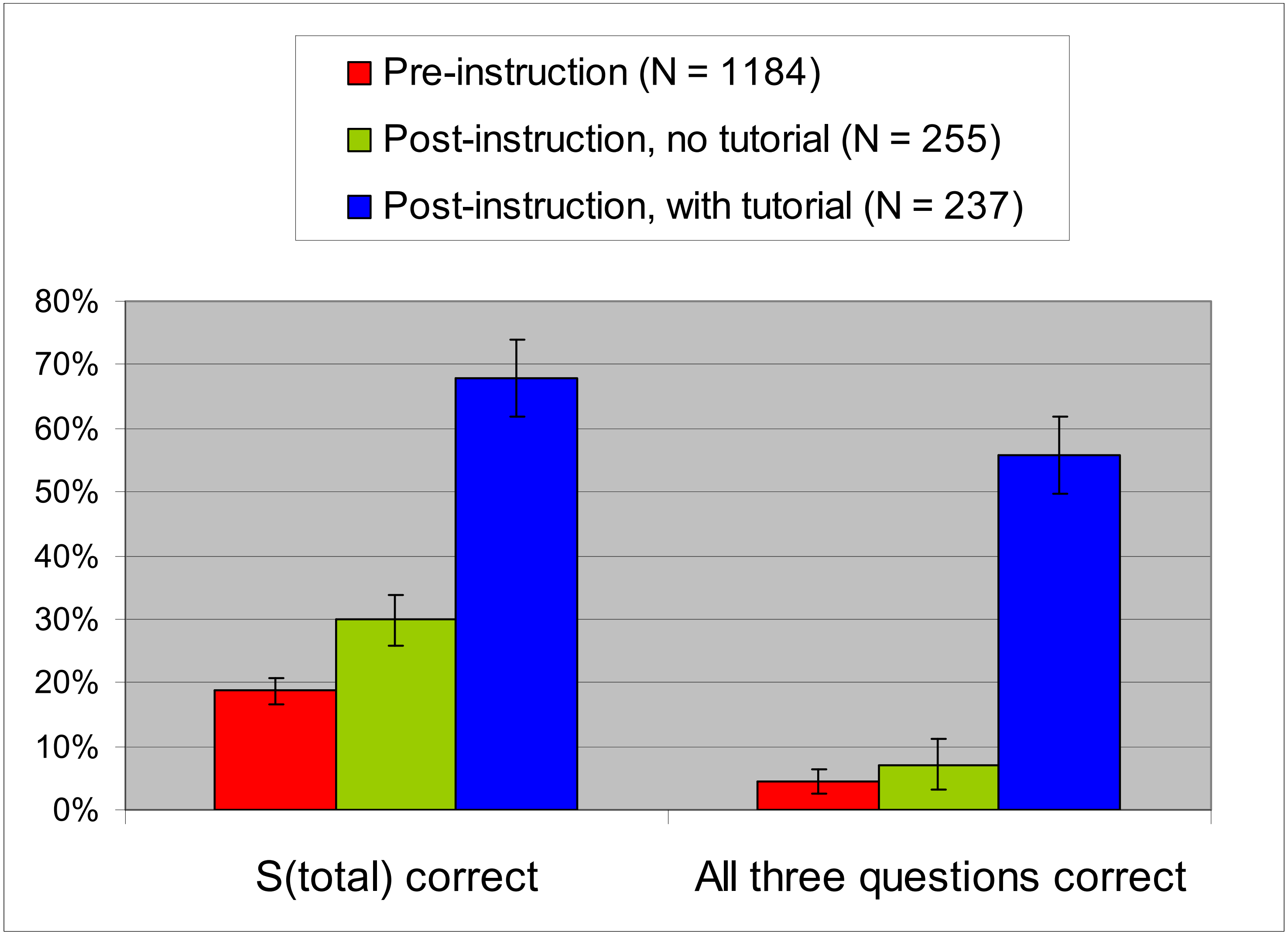
- Guide students to find that:

> Entropy gain of low-temperature block is *larger* than entropy loss of high-temperature block, so *total entropy increases*

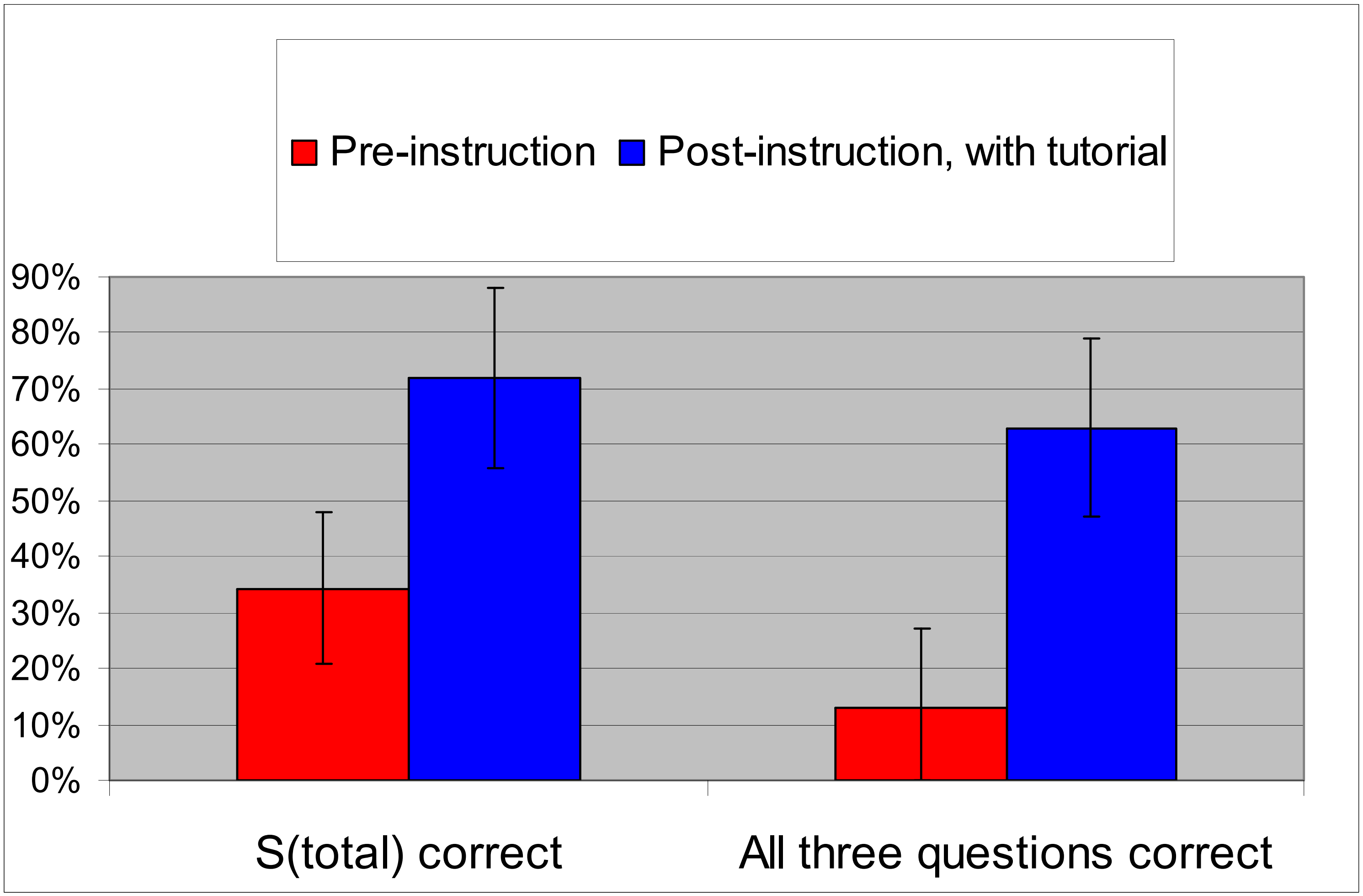
and that definitions of "system" and "surroundings" are arbitrary

> *Preliminary results are promising…*

Responses to General-Context Question
Introductory Students

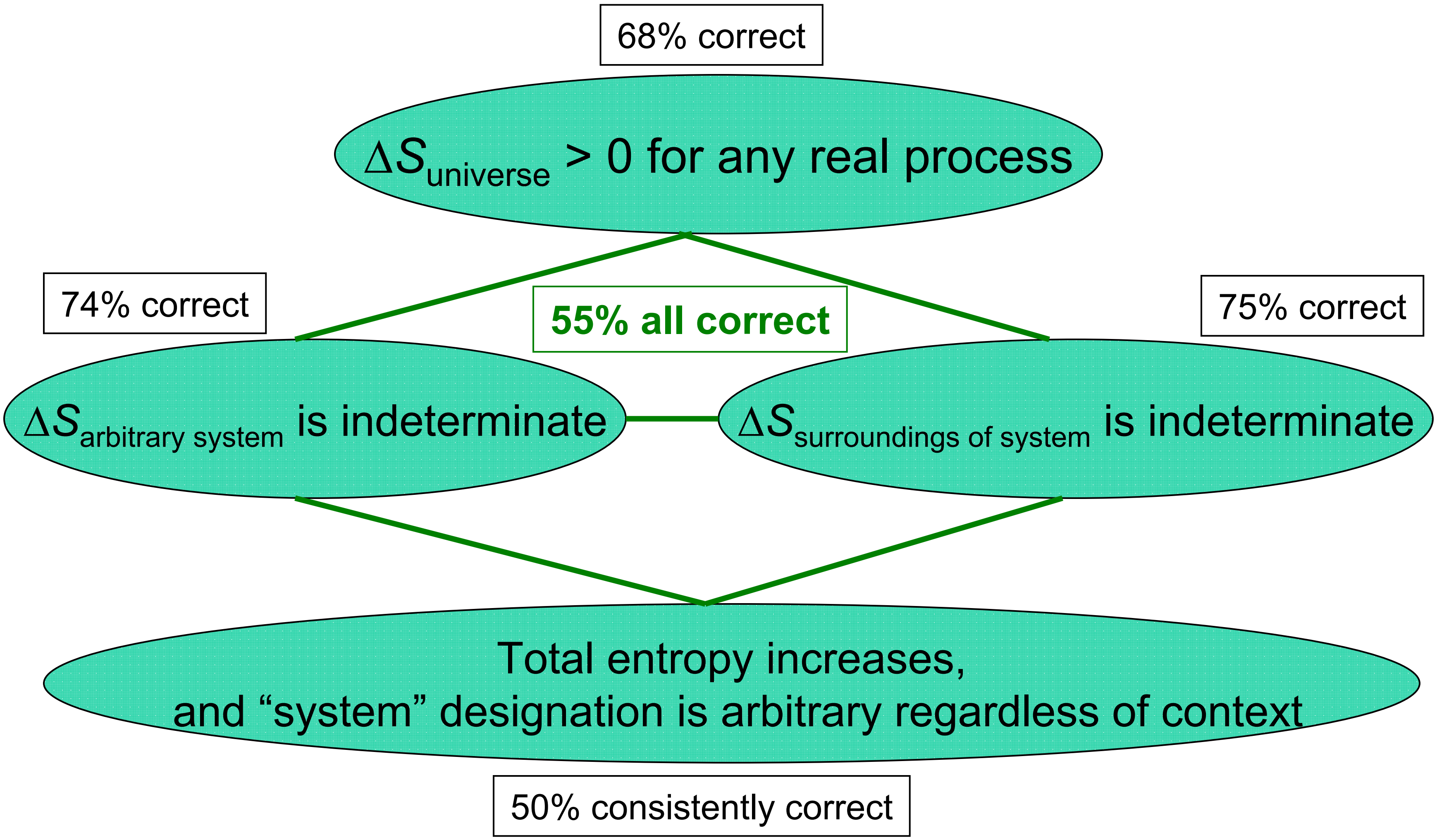


Responses to General-Context Question
Intermediate Students (*N* = 32, Matched)



Post-Instruction, With Research-Based Tutorial

[“Two-Blocks” Tutorial]



Summary

- Consistent results in many countries reveal substantial learning difficulties with fundamental concepts of thermal physics even after completion of introductory courses.
- Difficulties with fundamental concepts found among introductory physics students persist for many students beginning upper-level thermal physics course.
- Research-based instruction shows promise of improved performance, but learning difficulties in thermal physics tend to be difficult to address and slow to resolve.