Research on Student Learning in Thermal Physics

David E. Meltzer

College of Teacher Education and Leadership

Arizona State University

Mesa, Arizona, USA

Supported in part by U.S. National Science Foundation

Grant Nos. DUE 9981140, PHY 0406724, PHY 0604703, and DUE 0817282

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)

Funding

– NSF Division of Undergraduate Education
– 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 fundamental concepts, including heat, work, and 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 whose net change depend only on initial and final states.

- Students seem comfortable with this idea within the context of energy, temperature, and volume.[2]
- Students tend to overgeneralize the concept of state function and apply it inappropriately to properties such as heat and work.[1,2]
- Students have difficulty with the state-function property of entropy, believing net changes are process-dependent.[3,4]
- ***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: During expansion, system does positive work on surroundings and thereby loses energy; during compression, energy is transferred into system through work.

- Many students believe either that “no work” is done on the system[1] during an expansion (rather than negative work), or that the environment does *positive* work on the system.[2]
- Students fail to recognize that system loses energy through work done in an isobaric expansion[2], or that system gains energy through work done in an adiabatic compression.[1]
- ***Summary:*** Students retain learning difficulties with work concept acquired in introductory mechanics, and fail to recognize 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 in system, and intermolecular collisions have no net effect on 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, and that such collisions are responsible for system energy increases in an *isothermal* compression[2] or temperature increases in an *adiabatic* compression.[1,3,4]
- ***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 thermal energy that occur when system is in contact with a thermal “reservoir.”

- Students do not recognize that energy transfers must occur (through heat) in a quasistatic isothermal process.[2,4]
- Students do not recognize that a thermal reservoir does not, by definition, undergo temperature change even when acquiring energy through heat transfer.[2]
- ***Summary:*** Students fail to recognize idealizations involved in definitions of “reservoir” and “isothermal process,” and so become unable to analyze the primary physical mechanisms responsible for such processes.

[2]Meltzer, 2004

[4]Leinonen et al., 2009

Target Concept 5: Both heat transfer to, and work done by a system are process-dependent quantities, and net values of each in an arbitrary cyclic process are non-zero.

- Students believe that heat transfers to a system that undergoes two different processes linking the same initial and final states must be equal, and that net heat transfer in a cyclic process must be zero since $\Delta T = 0$.[2]
- Many students believe that work done by a system that undergoes two different processes linking the same initial and final states must be equal, and that net work done in a cyclic process must be zero since $\Delta V = 0$.[1,2]
- ***Summary:*** Students fail to recognize that neither heat nor work is or behaves as 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

Previous Phase of Current Project:
Student Learning of Thermodynamics in Introductory Physics

- Investigation of 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*
  - *final grades of interview sample far above class average*

Primary Findings, Introductory Course

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

- believe that heat and/or work are state functions independent of process
- believe that net work done and net heat absorbed by a system undergoing a cyclic process must be zero
- are unable to apply the First Law of Thermodynamics in problem solving

Thermal Physics: Course and Students

- **Topics:** Approximately equal balance between classical macroscopic thermodynamics, and statistical thermodynamics (Texts: Sears and Salinger; Schroeder)
- **Students enrolled** [$N_{initial}$ = 14 (*2003*) and 19 (*2004*)]
  - ≈ 90% were physics majors or physics/engineering double majors
  - ≈ 90% were juniors or above
  - all had studied thermodynamics (some at advanced level)

Course taught by DEM using lecture + interactive-engagement

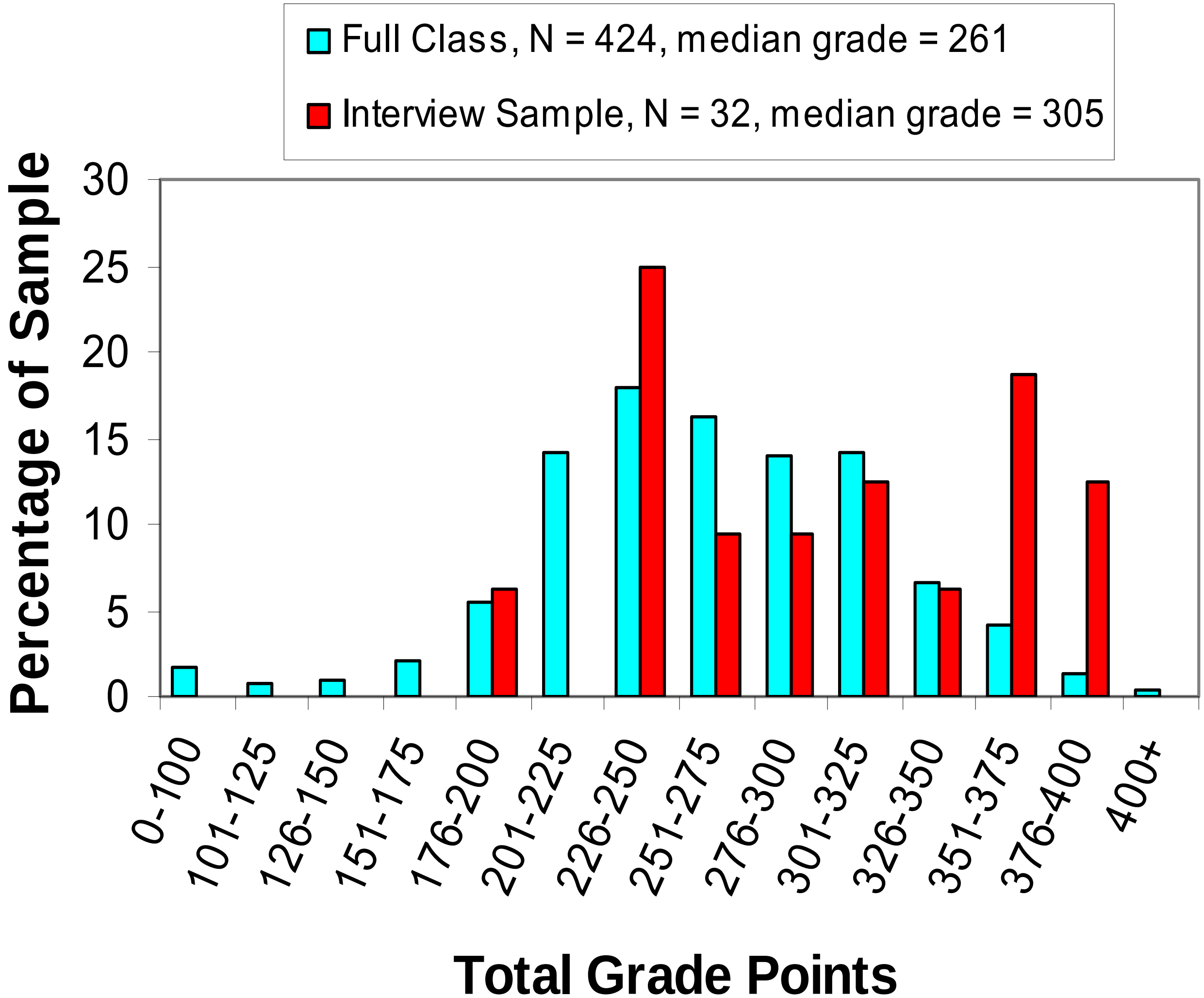
Performance Comparison: Upper-level vs. Introductory Students

- Diagnostic questions given to students in introductory calculus-based course *after* instruction was complete:
  - 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 Thermal Physics students on first day of class

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 Thermal Physics students on first day of class

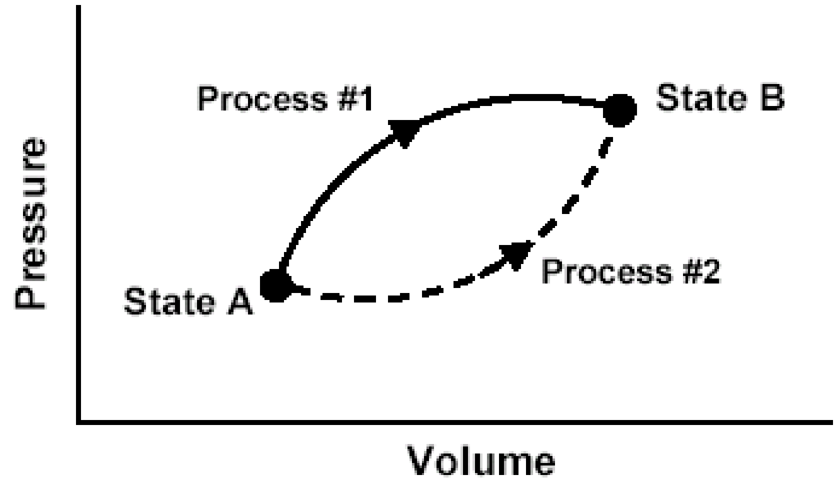
Grade Distributions: Interview Sample vs. Full Class



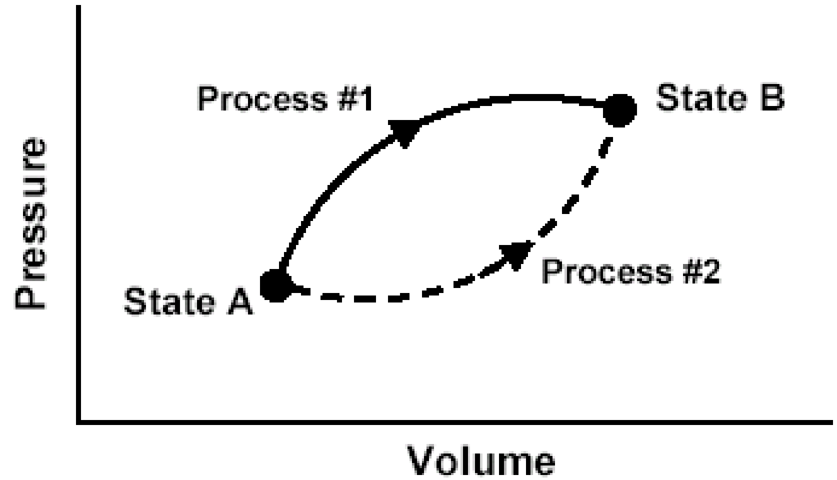
***Interview Sample*:**

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:



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

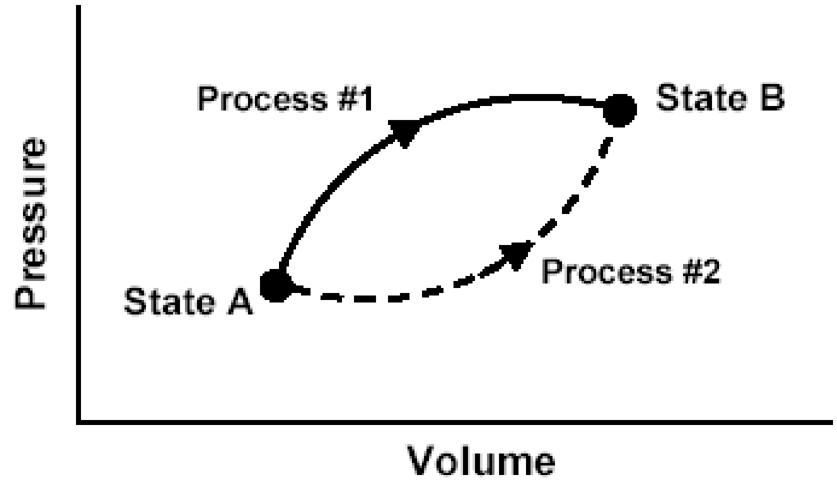


[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

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

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



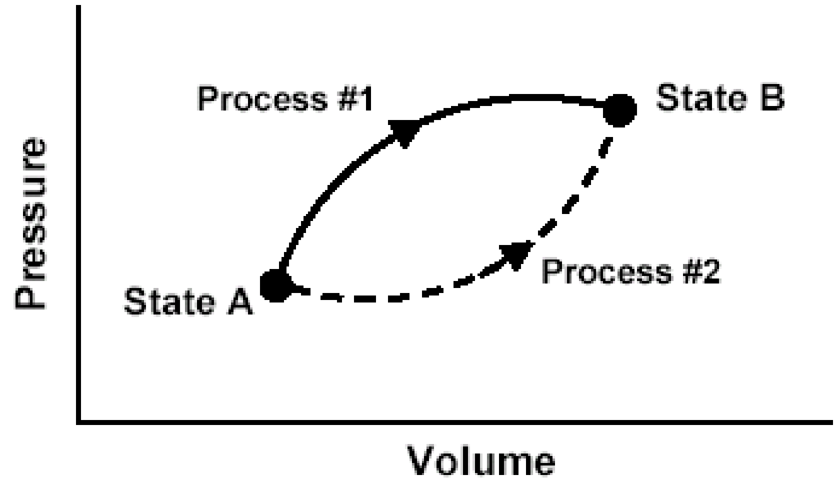
[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

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

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:

$$W = \int_{V_A}^{V_B} P\,dV$$



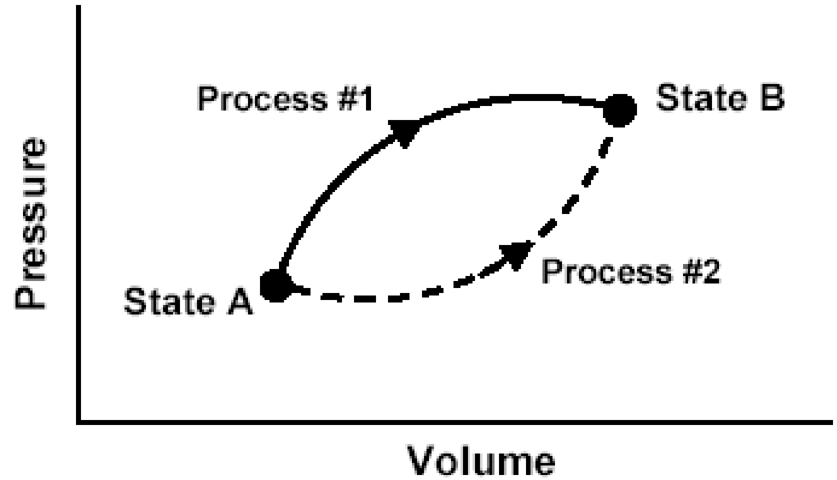
[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

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

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:

$$W = \int_{V_A}^{V_B} P\,dV$$



$$W_1 > W_2$$

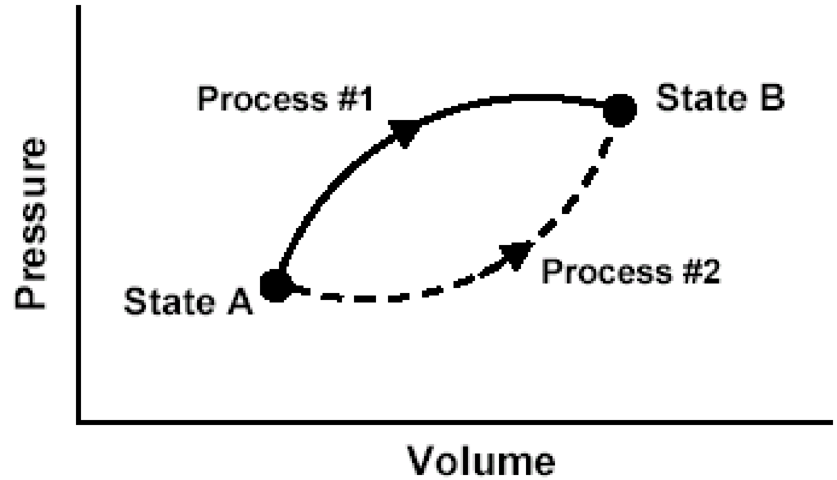
[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

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

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:

$$W = \int_{V_A}^{V_B} P\,dV$$



$$W_1 > W_2$$

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

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

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

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
(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** Thermal Physics (Pretest) (N=14)
$W_1 = W_2$	**30%**	**22%**	**20%**

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

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

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

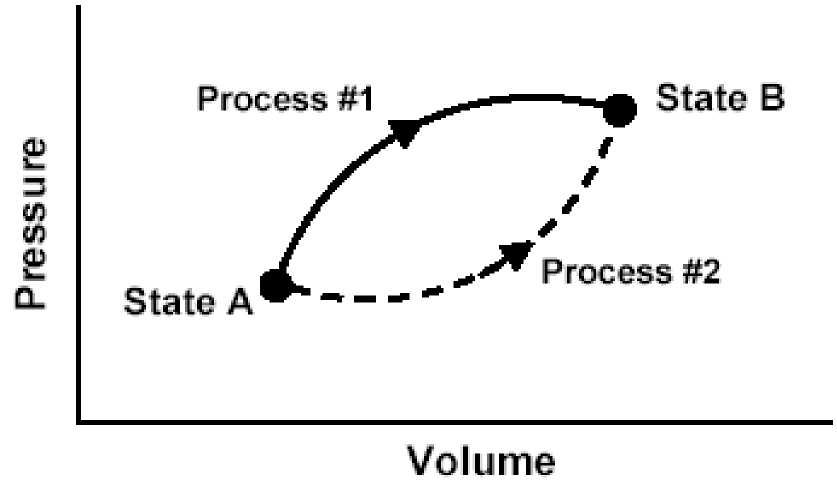
Explanations Given by Thermal Physics Students to Justify $W_1 = W_2$

- "*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.**

Confusion with mechanical work done by conservative forces?

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

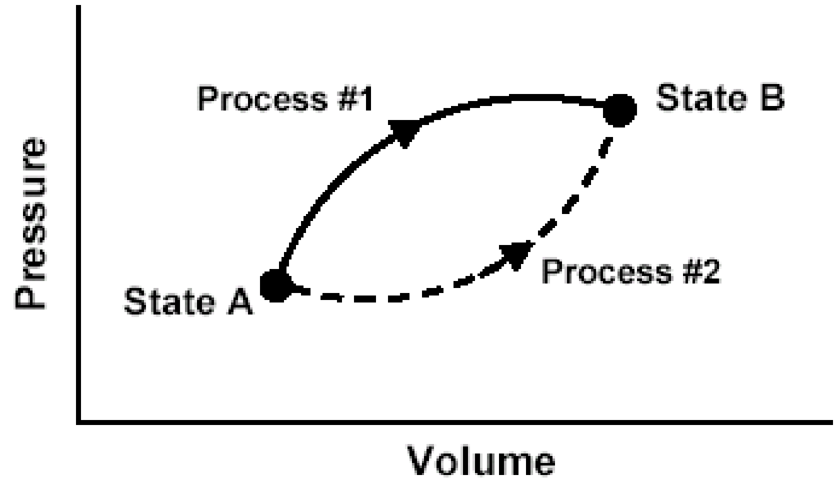


[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

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

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



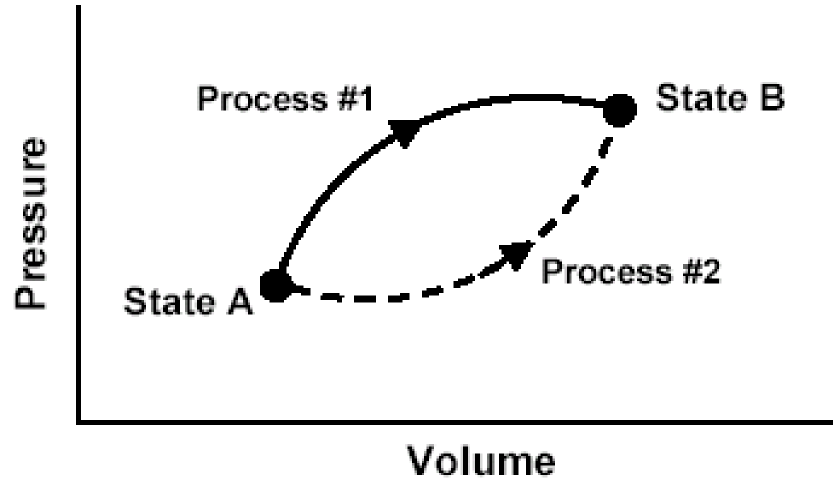
[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

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

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.



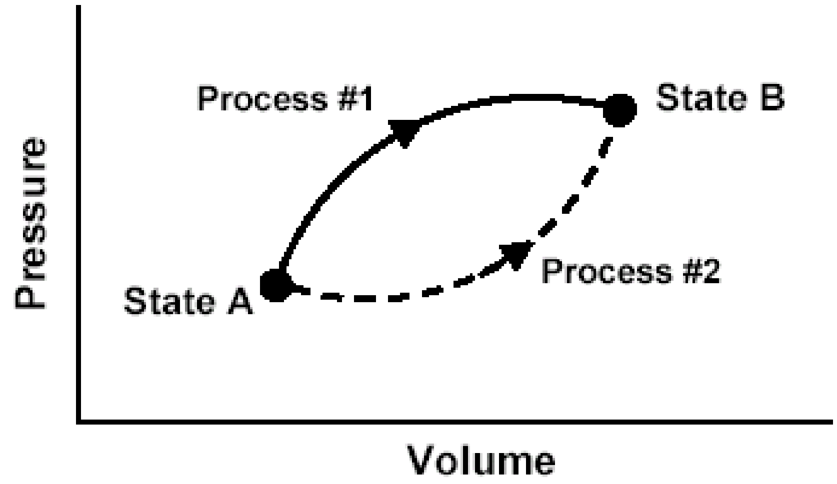
[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

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

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:
$Q_1 > Q_2$



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

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

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

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.**

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)

$Q_1 > Q_2$			
[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)

	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%
Correct or partially correct explanation	11%	19%	30%

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

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

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

Cyclic Process Questions

Cyclic Process Questions

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

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.

Cyclic Process Questions

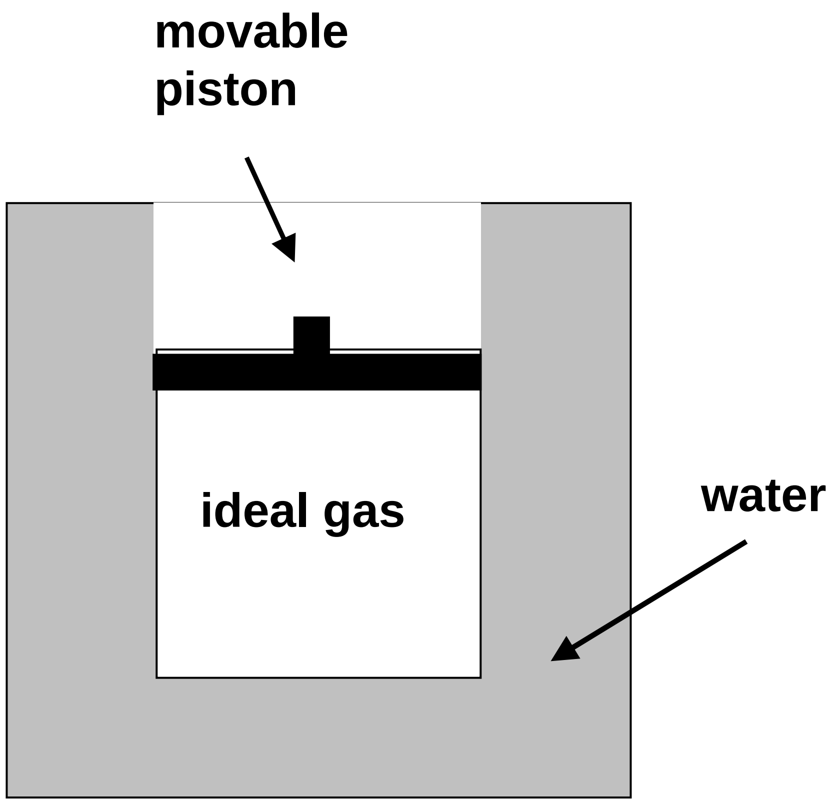
A fixed quantity of ideal gas is contained within a metal cylinder that is sealed with a movable, frictionless, insulating piston.

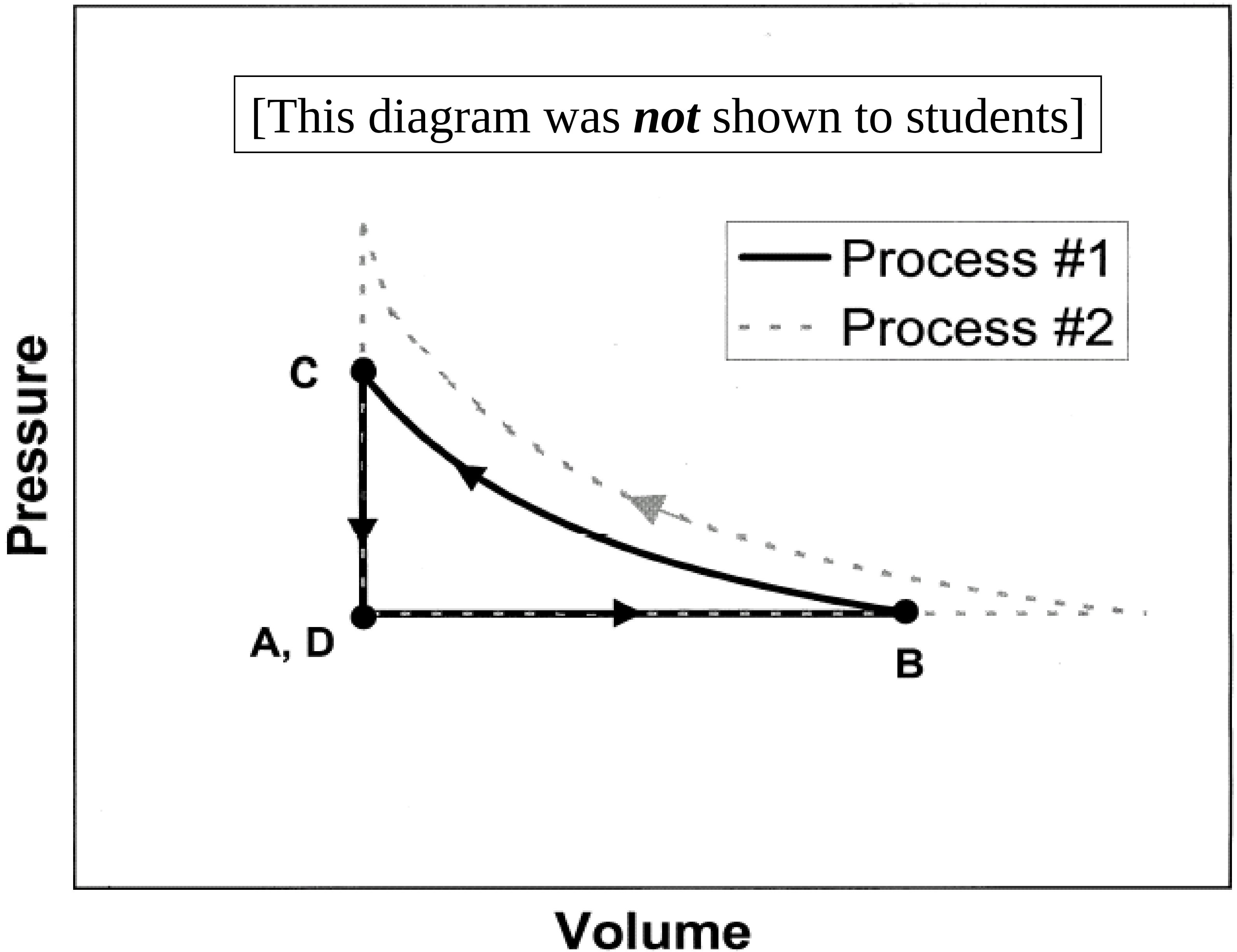
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

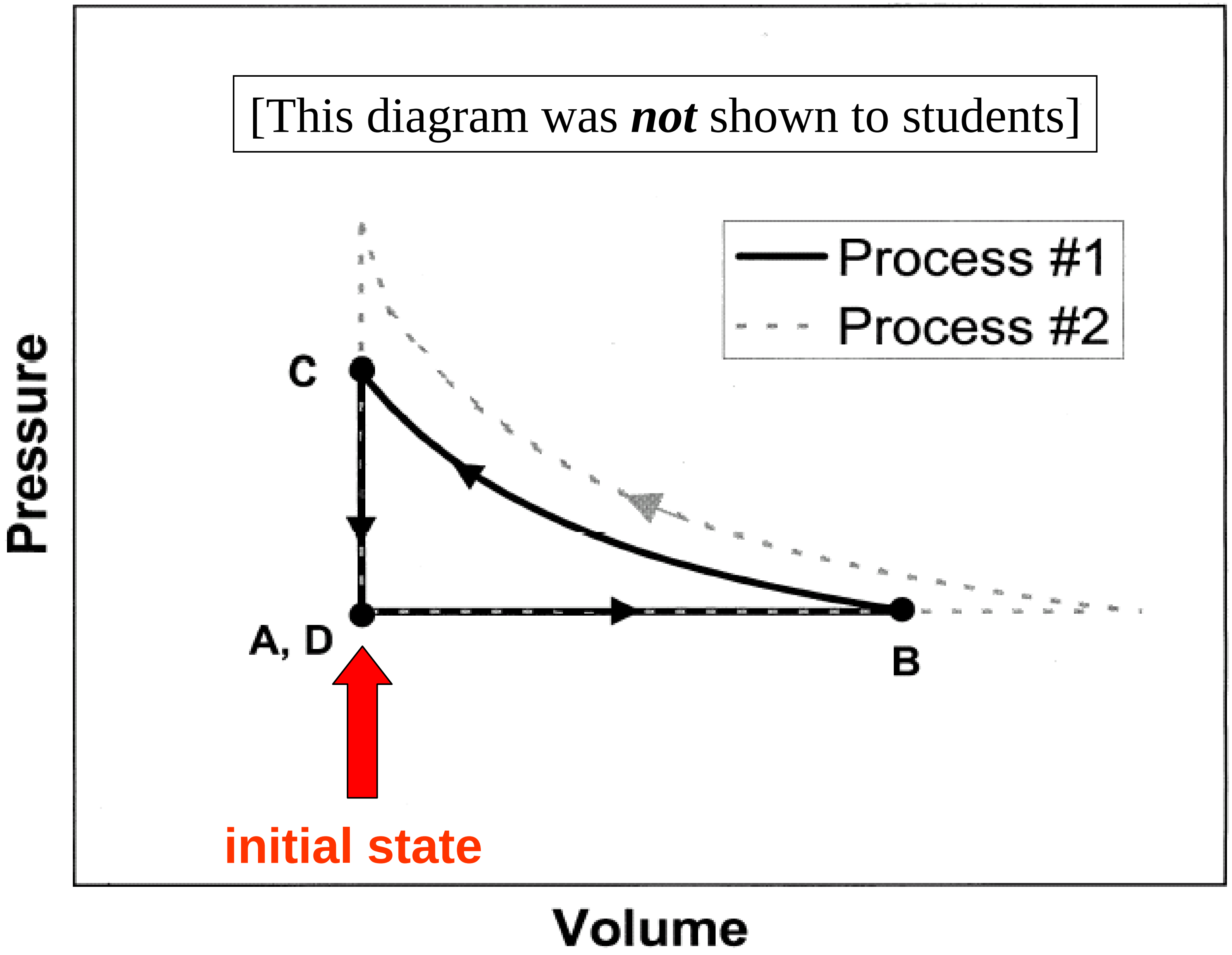
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature

Time *A*

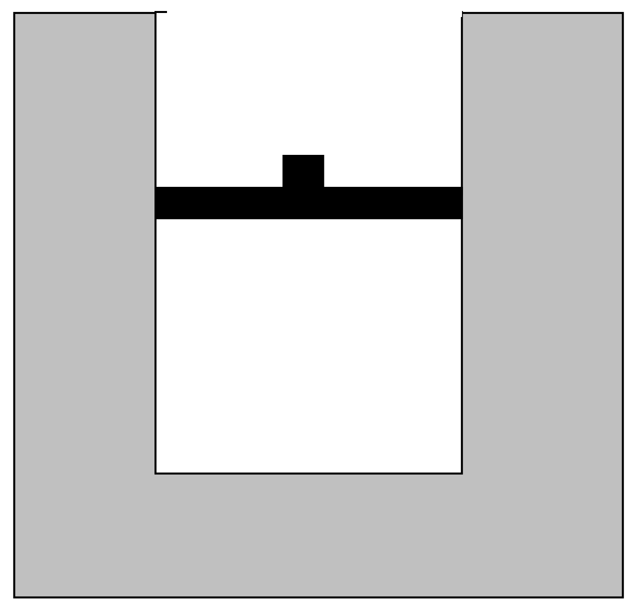
Entire system at room temperature.

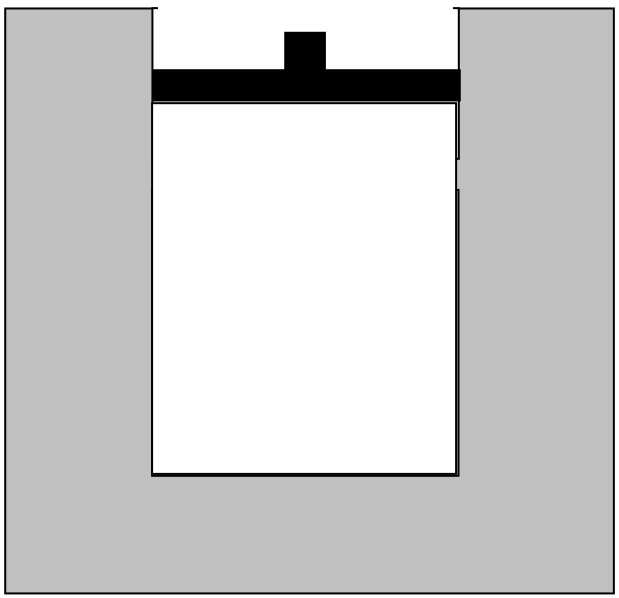



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

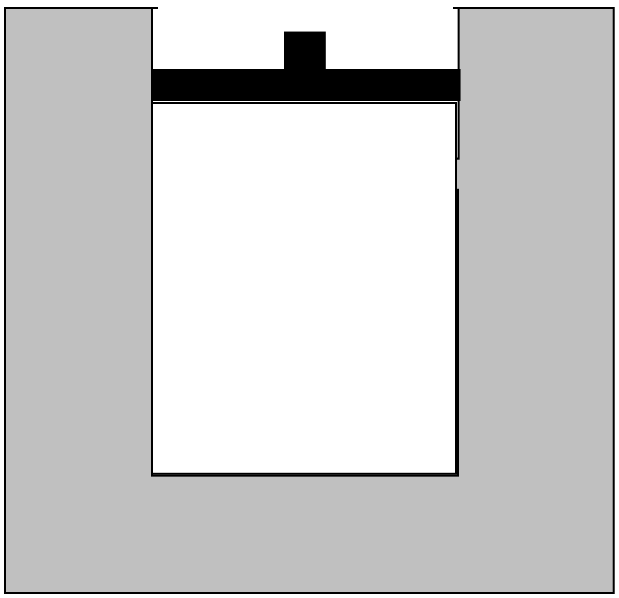

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
initial state
Pressure
Volume

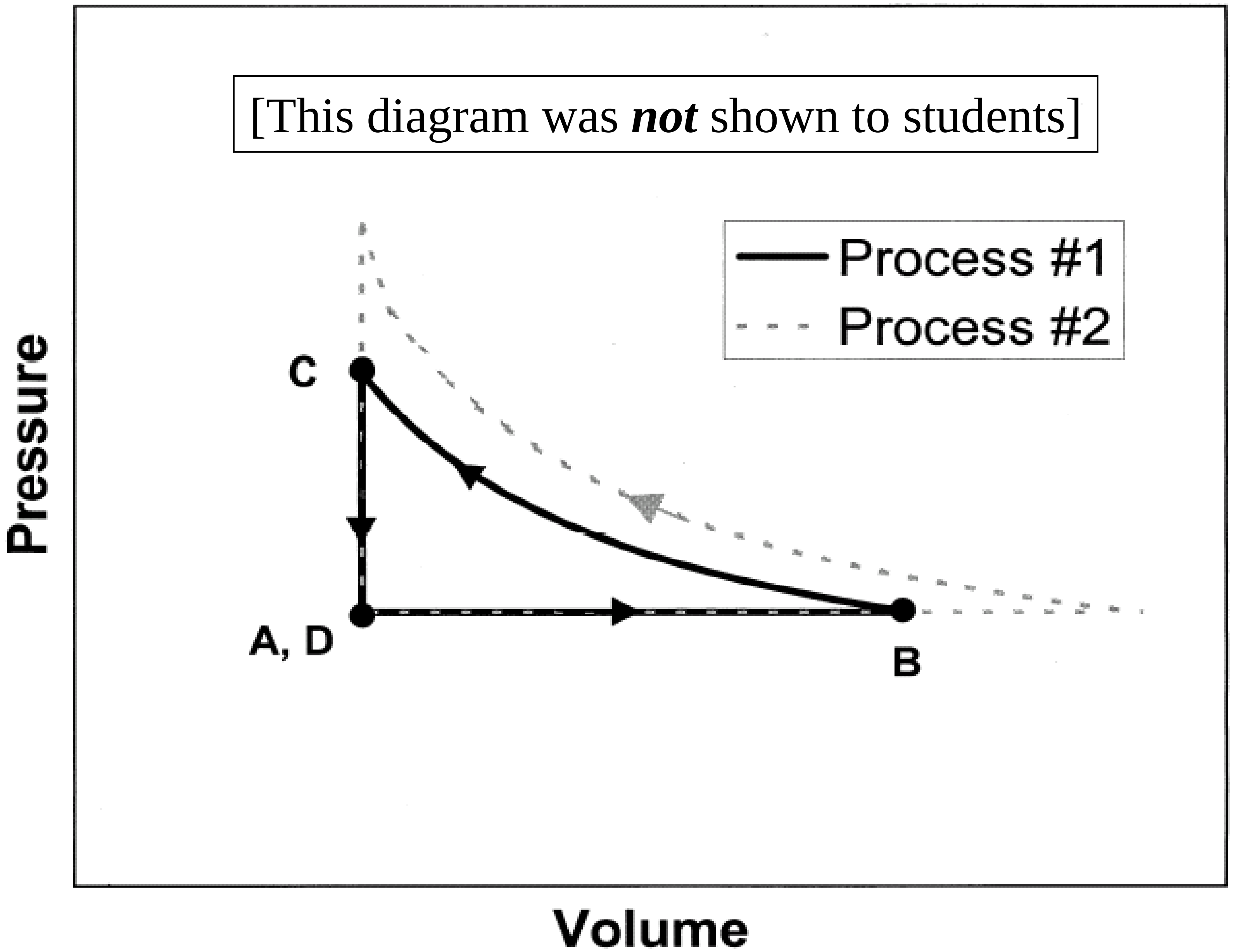
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.

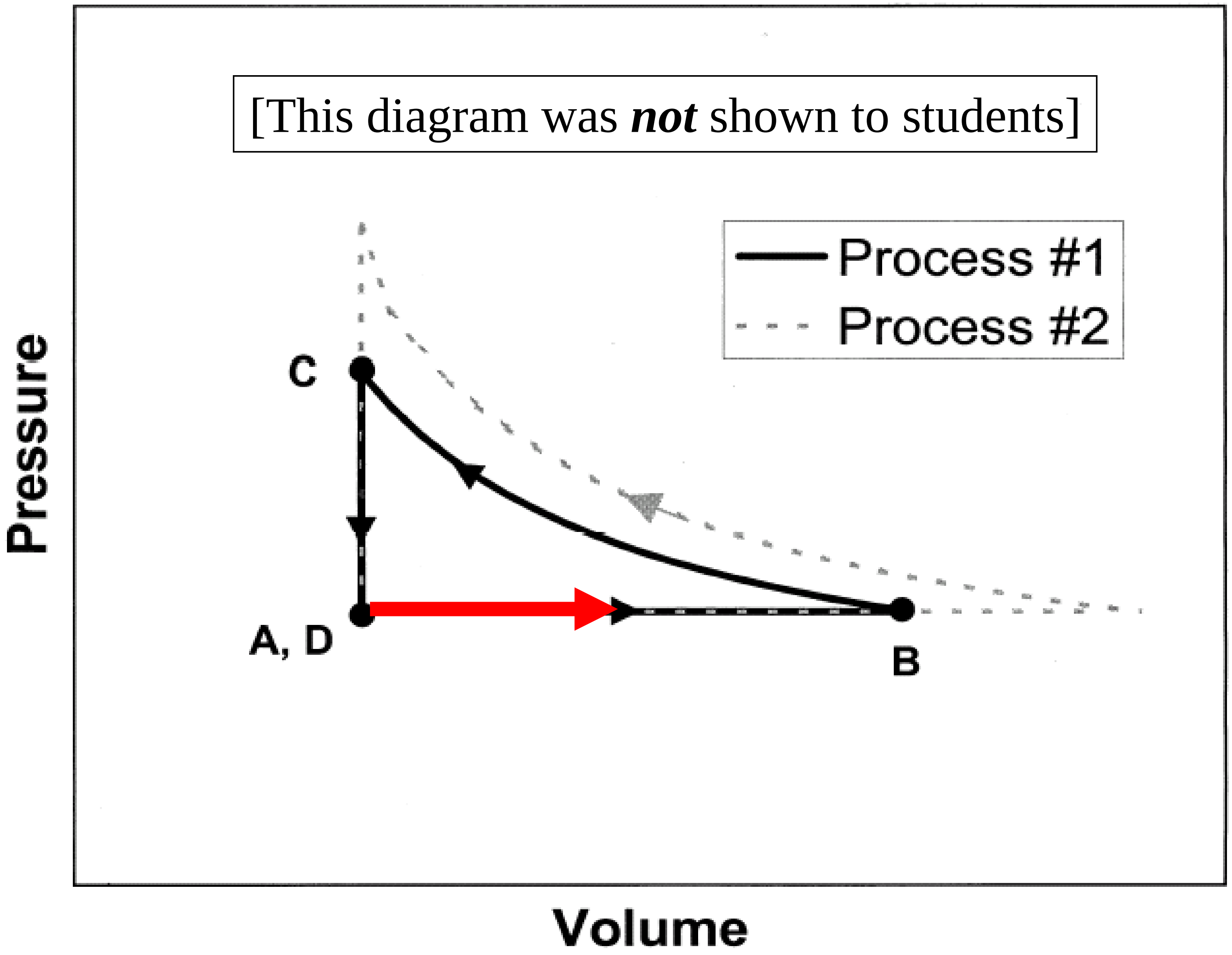




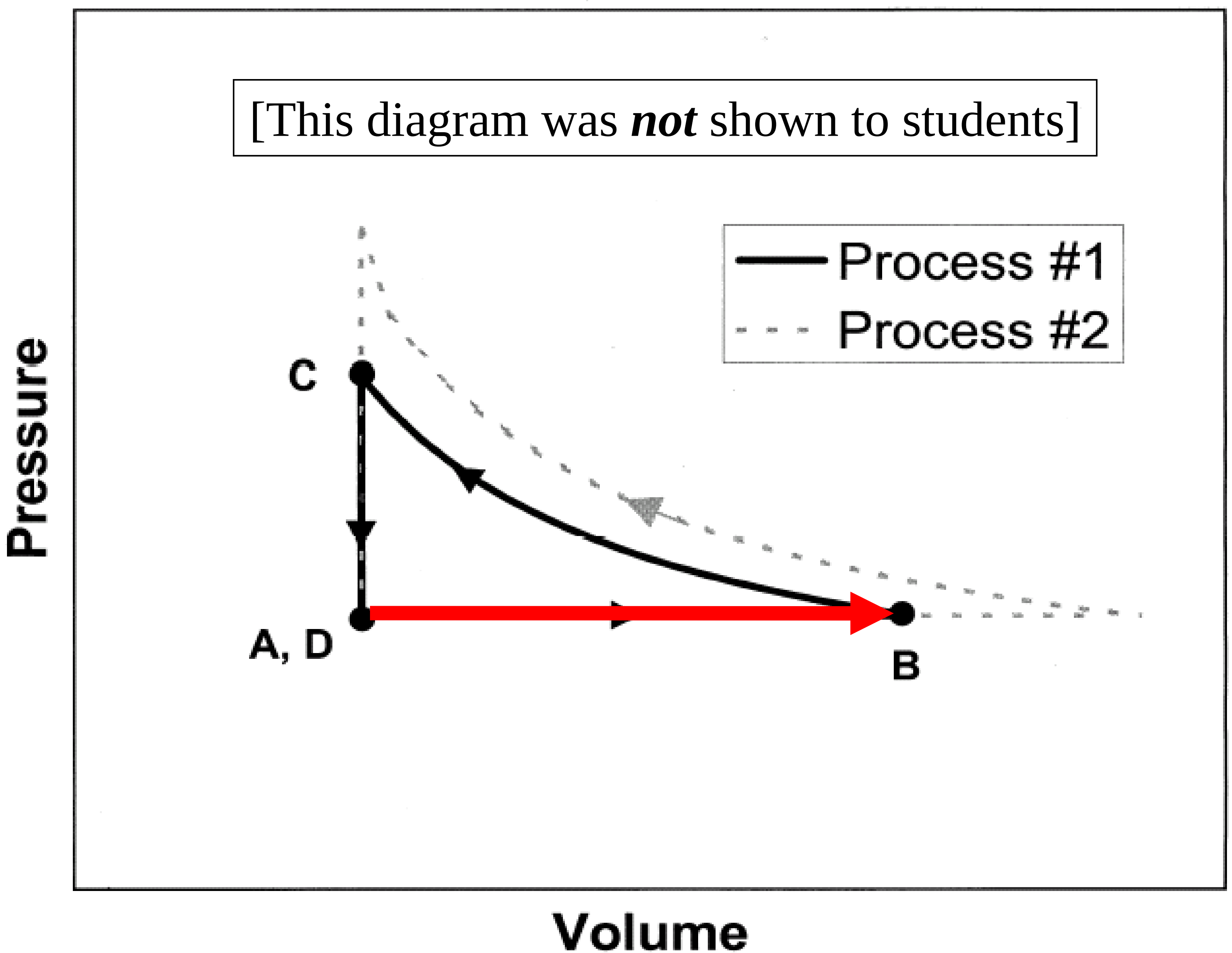
At time ***B*** the heating of the water stops, and the piston stops moving

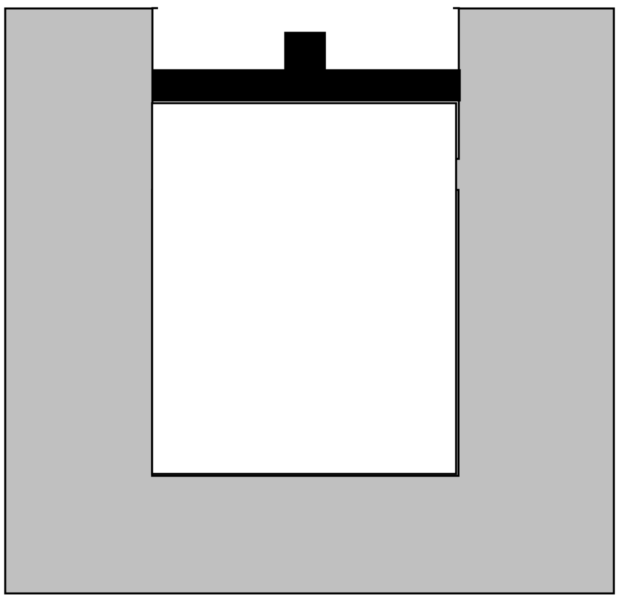


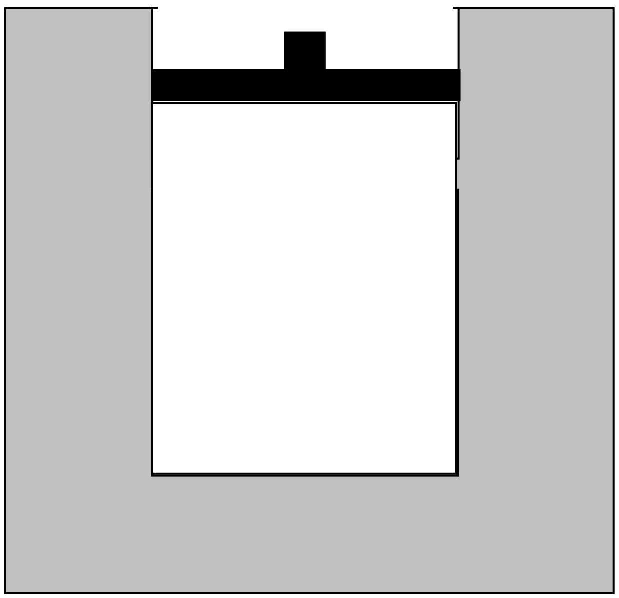

[This diagram was not shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



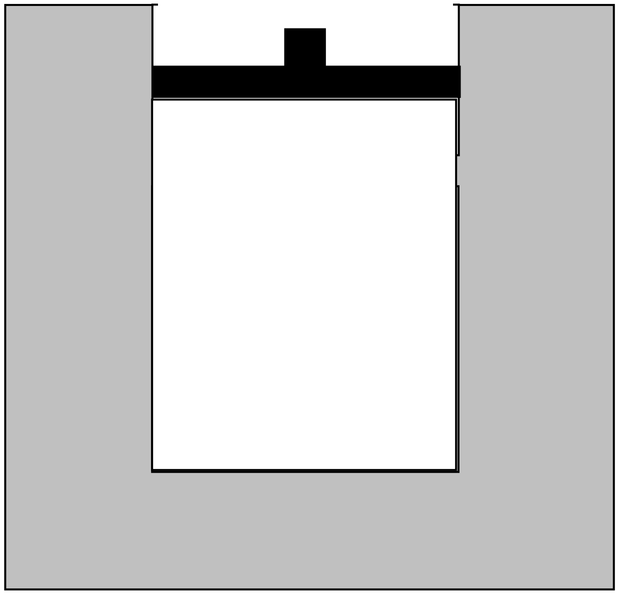
[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume


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





Question #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.



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.

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

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

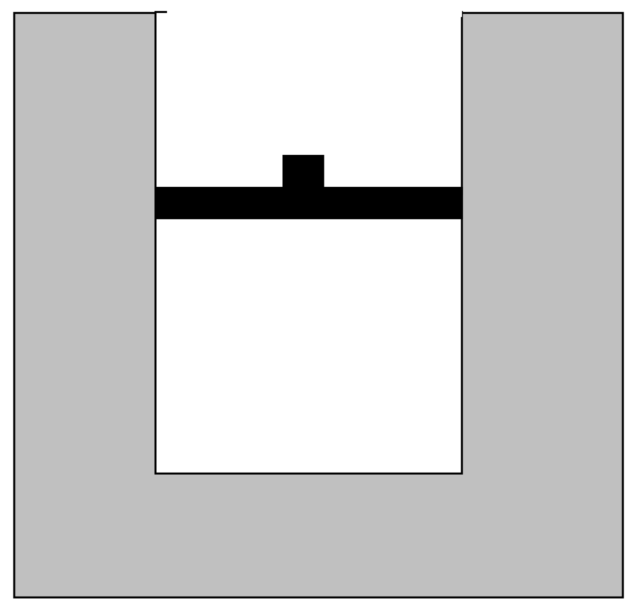
- Basic notion of thermodynamics: if part or all of system boundary is displaced during quasistatic process, energy is transferred between system and surroundings in the form of “work.”

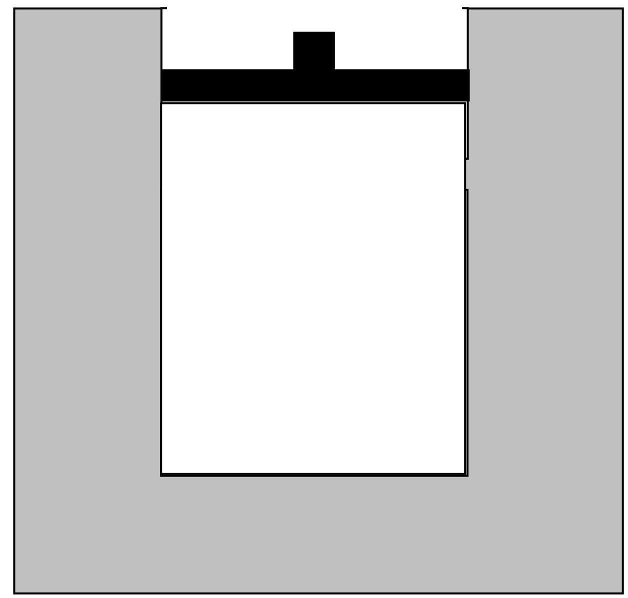
Failure to Recognize "Work" as a Mechanism of Energy Transfer

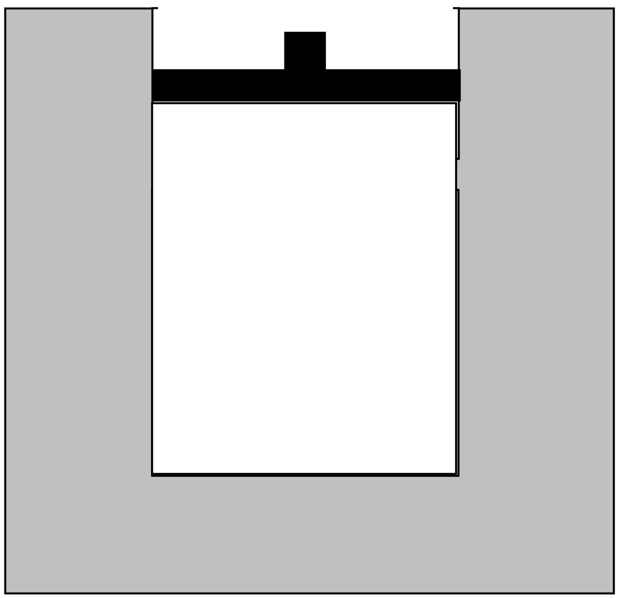
- Basic notion of thermodynamics: if part or all of system boundary is displaced during quasistatic process, energy is transferred between system and surroundings in the form of "work."
- Study of Loverude, Kautz, and Heron (2002) showed that few students could spontaneously invoke concept of work in case of adiabatic compression.

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

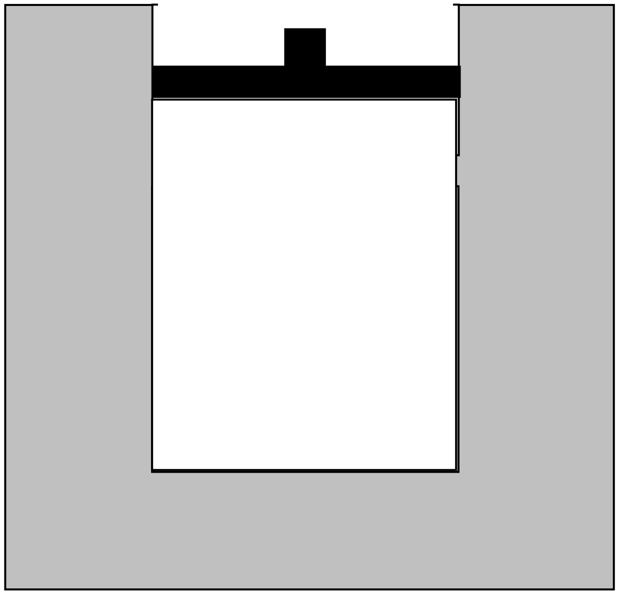
- Basic notion of thermodynamics: if part or all of system boundary is displaced during quasistatic process, energy is transferred between system and surroundings in the form of “work.”
- Study of Loverude, Kautz, and Heron (2002) showed that few students could spontaneously invoke concept of work in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







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.



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

Results on Question #1

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

(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

(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.”

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.”

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."

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

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."

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

Results on Question #1

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

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

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

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

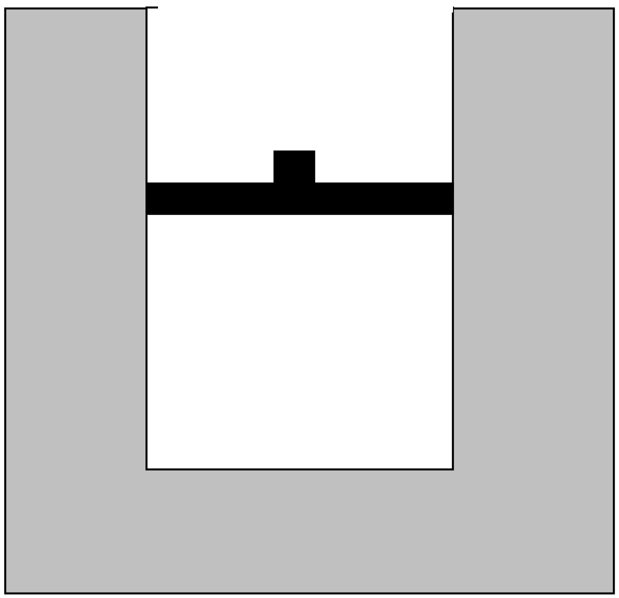
Sample explanations for (a) answer:

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

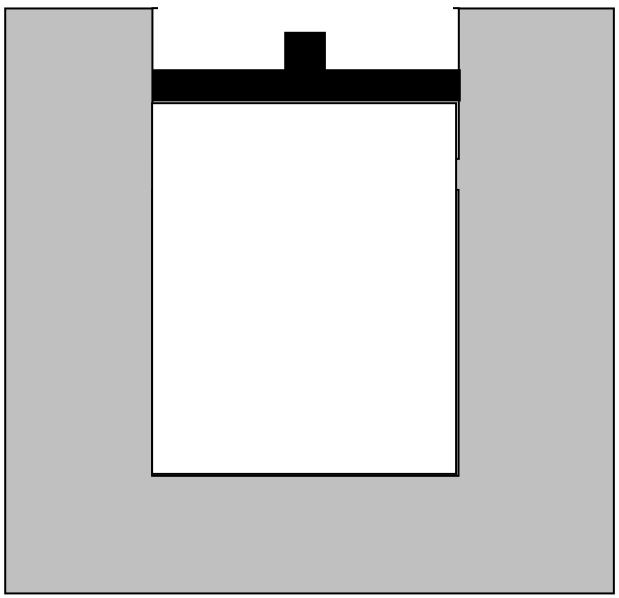
"The environment did work on the gas, since it made the gas expand and the piston moved up . . . water was heating up, doing work on the gas, making it expand."

→ *Additional questions showed that half the sample did not know that some energy was transferred away from gas during expansion .*

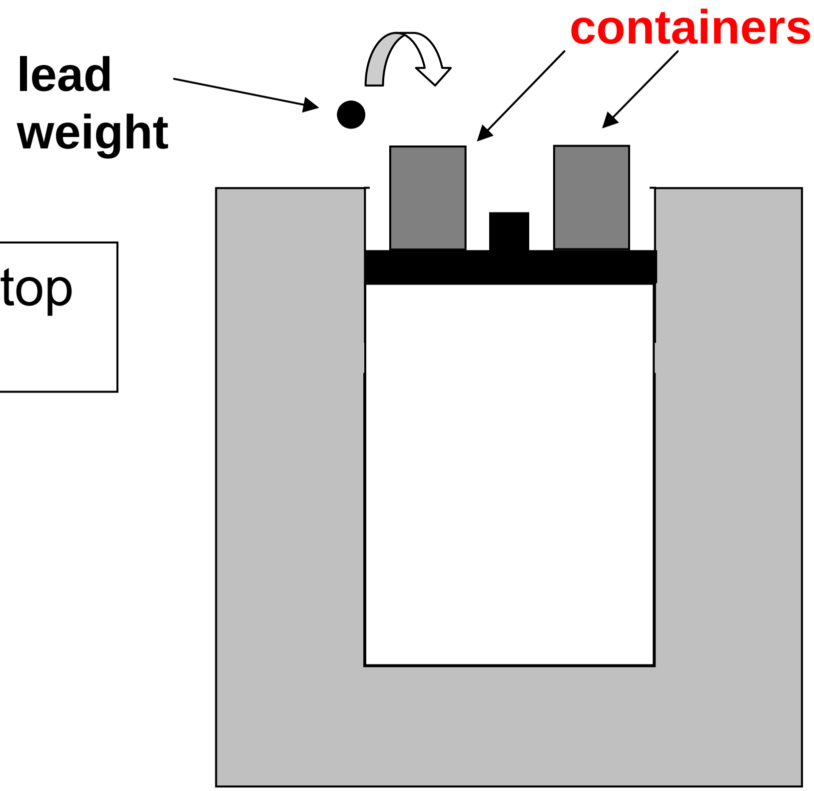
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.



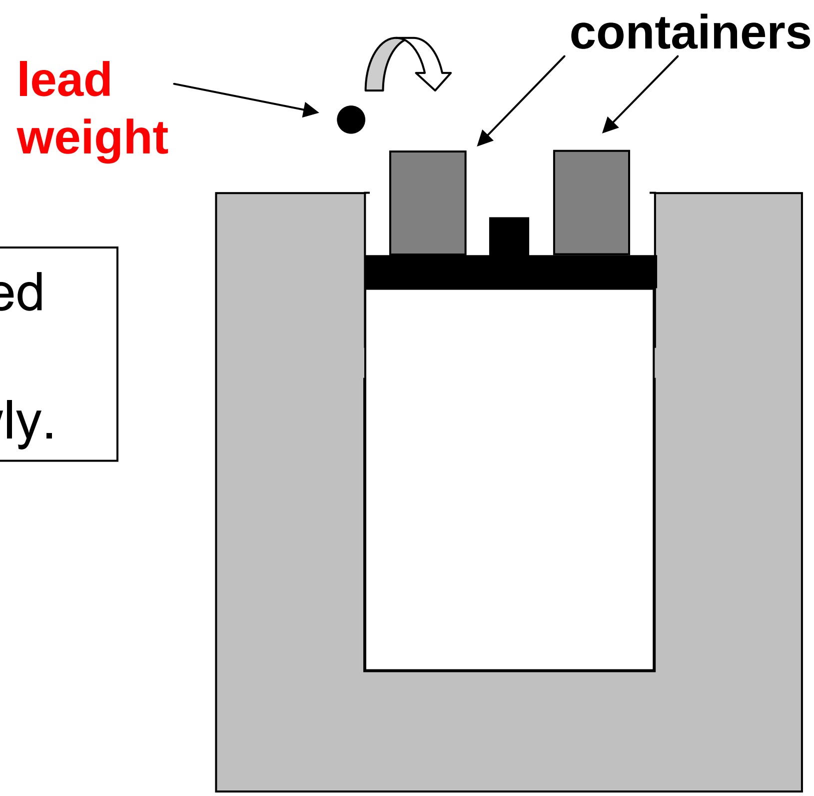
At time ***B*** the heating of the water stops, and the piston stops moving

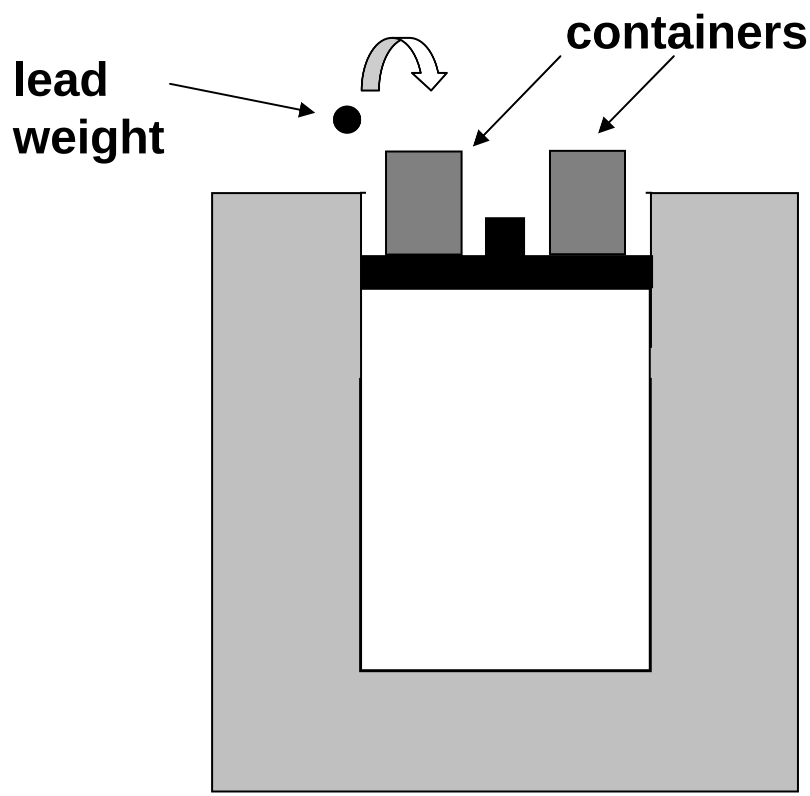


Now, empty containers are placed on top of the piston as shown.

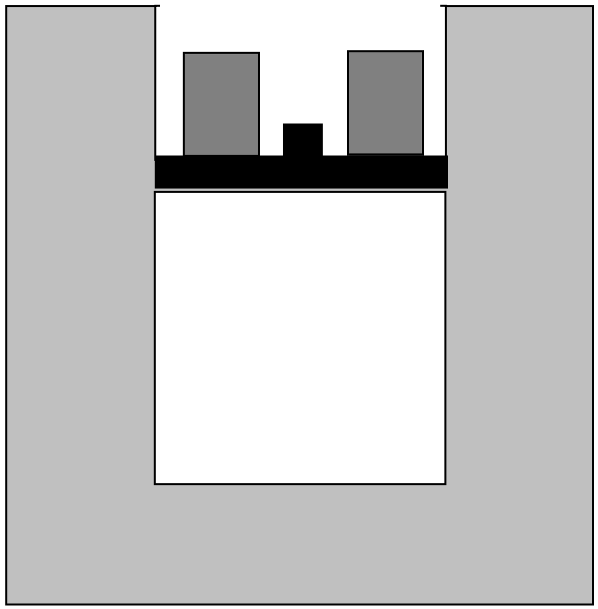


Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly.

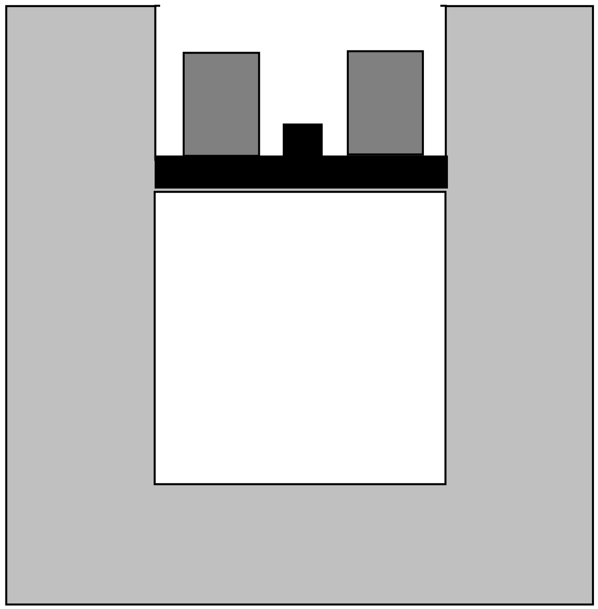




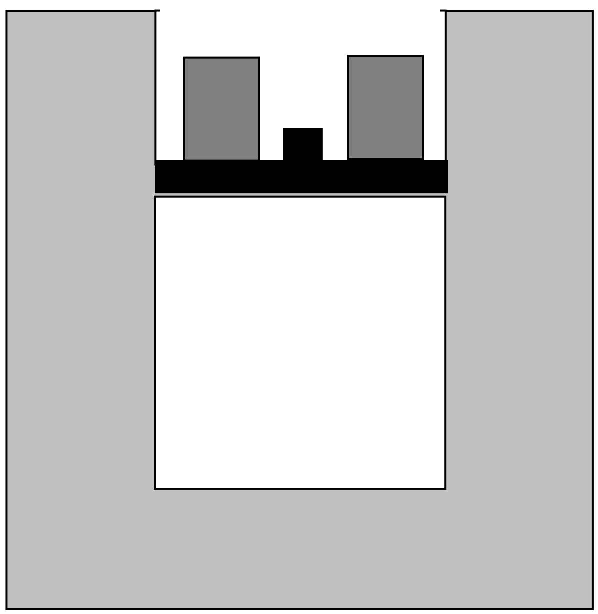
lead
weight
containers

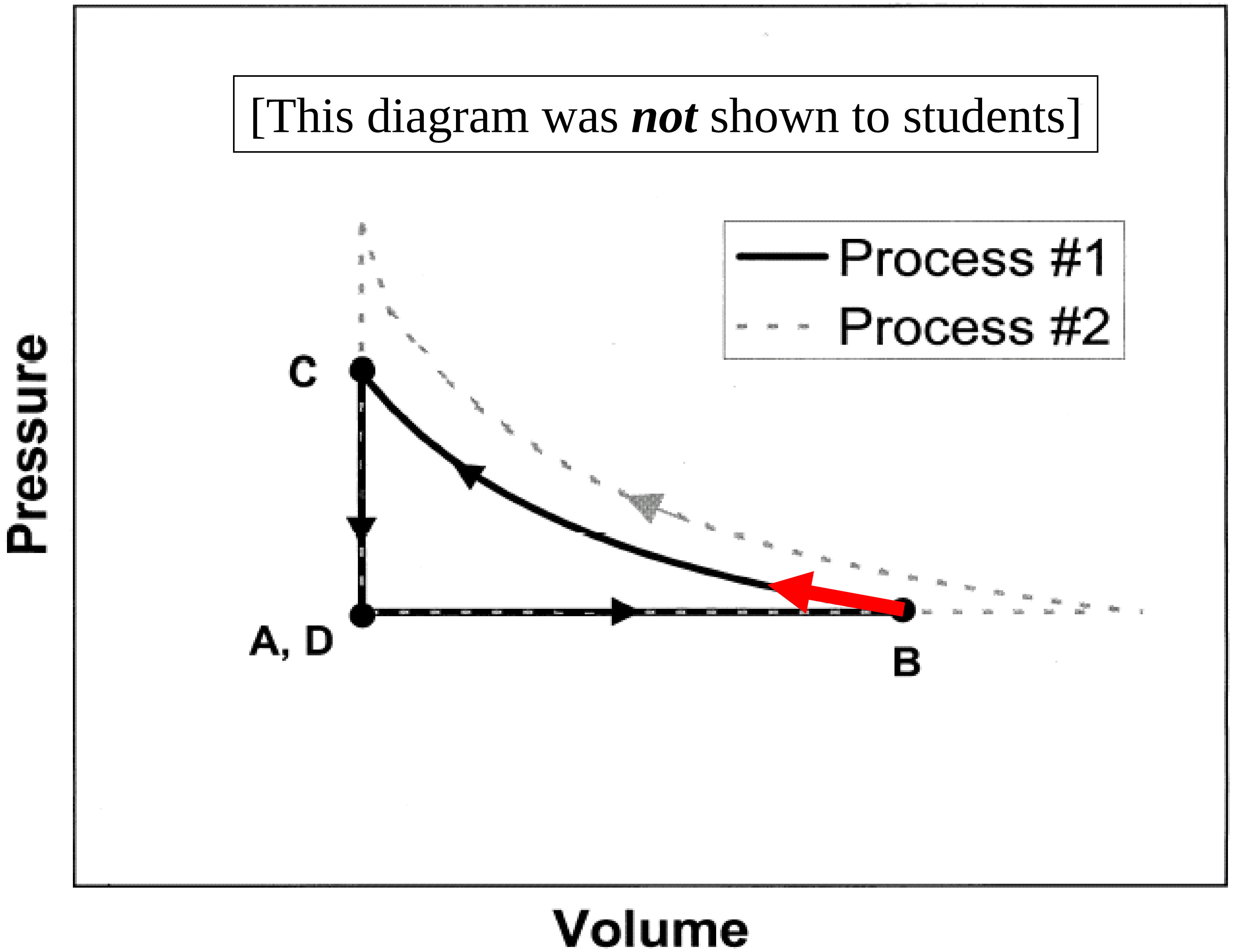


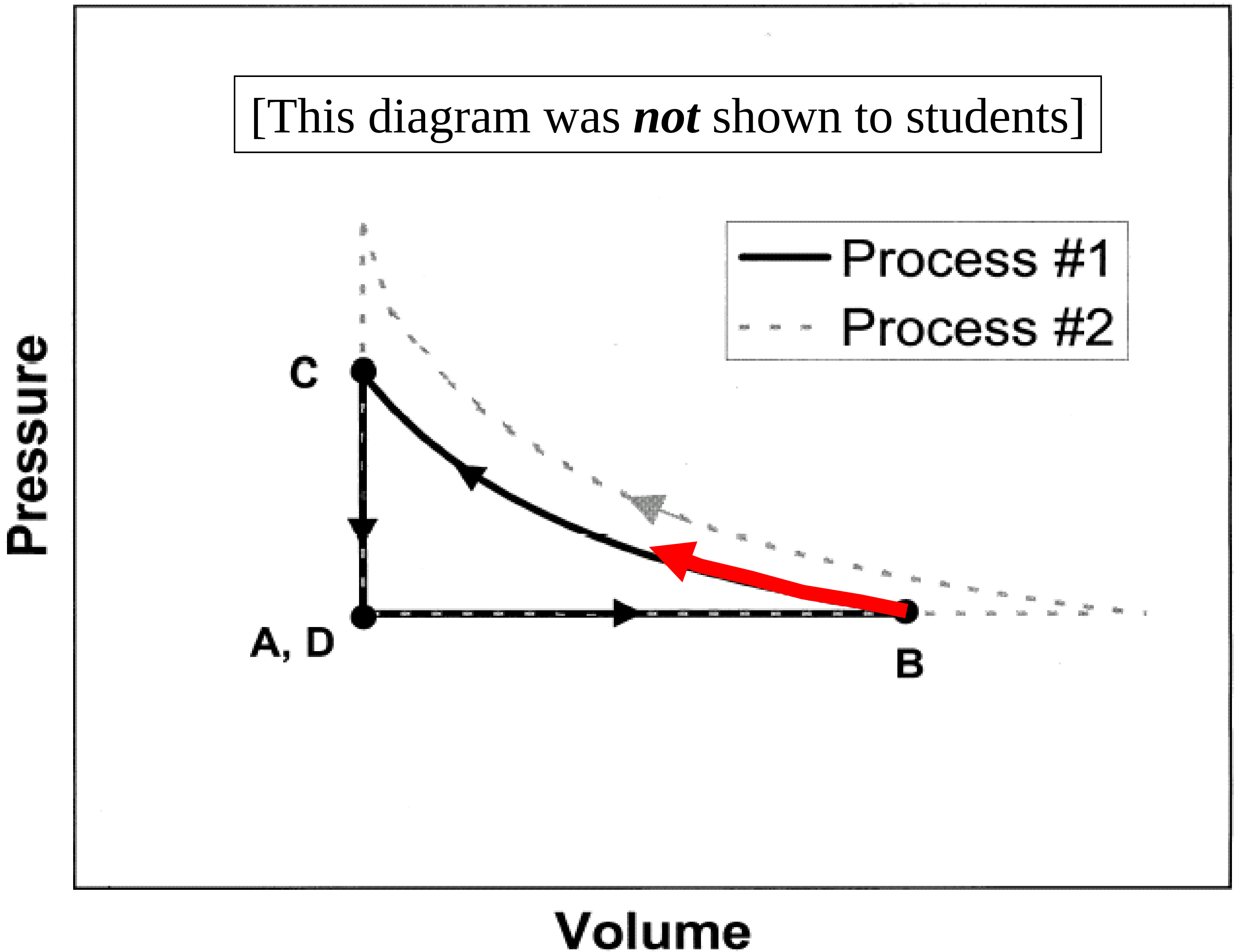
While this happens the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*.

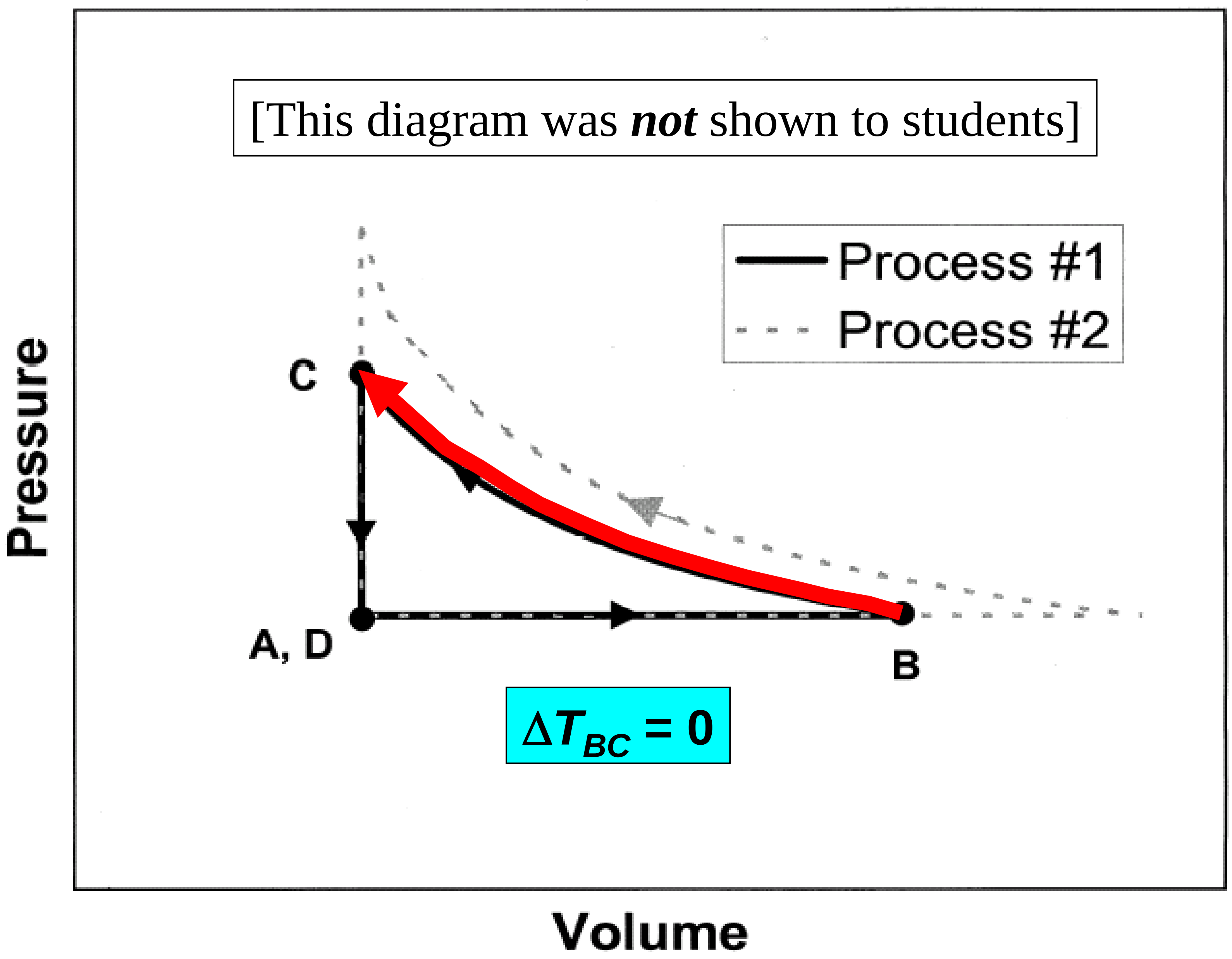


At time ***C*** we stop adding lead weights to the container and the piston stops moving. The piston is now at exactly the same position it was at time ***A*** .

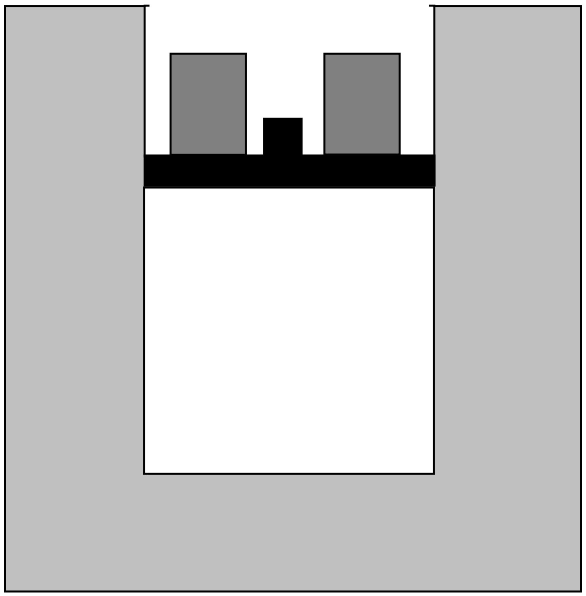



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

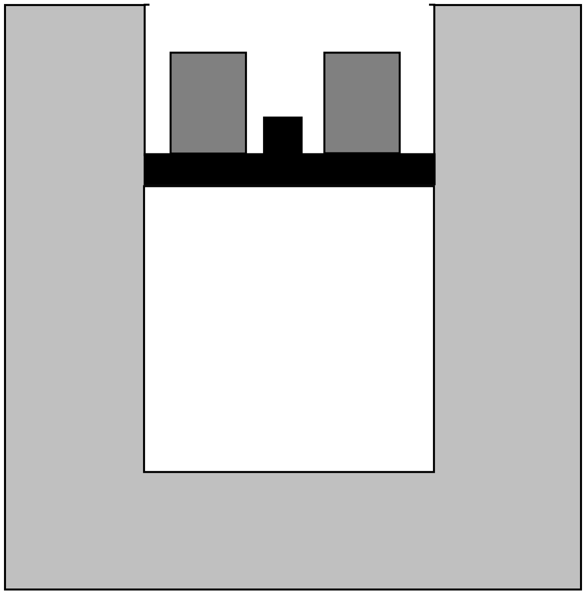

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



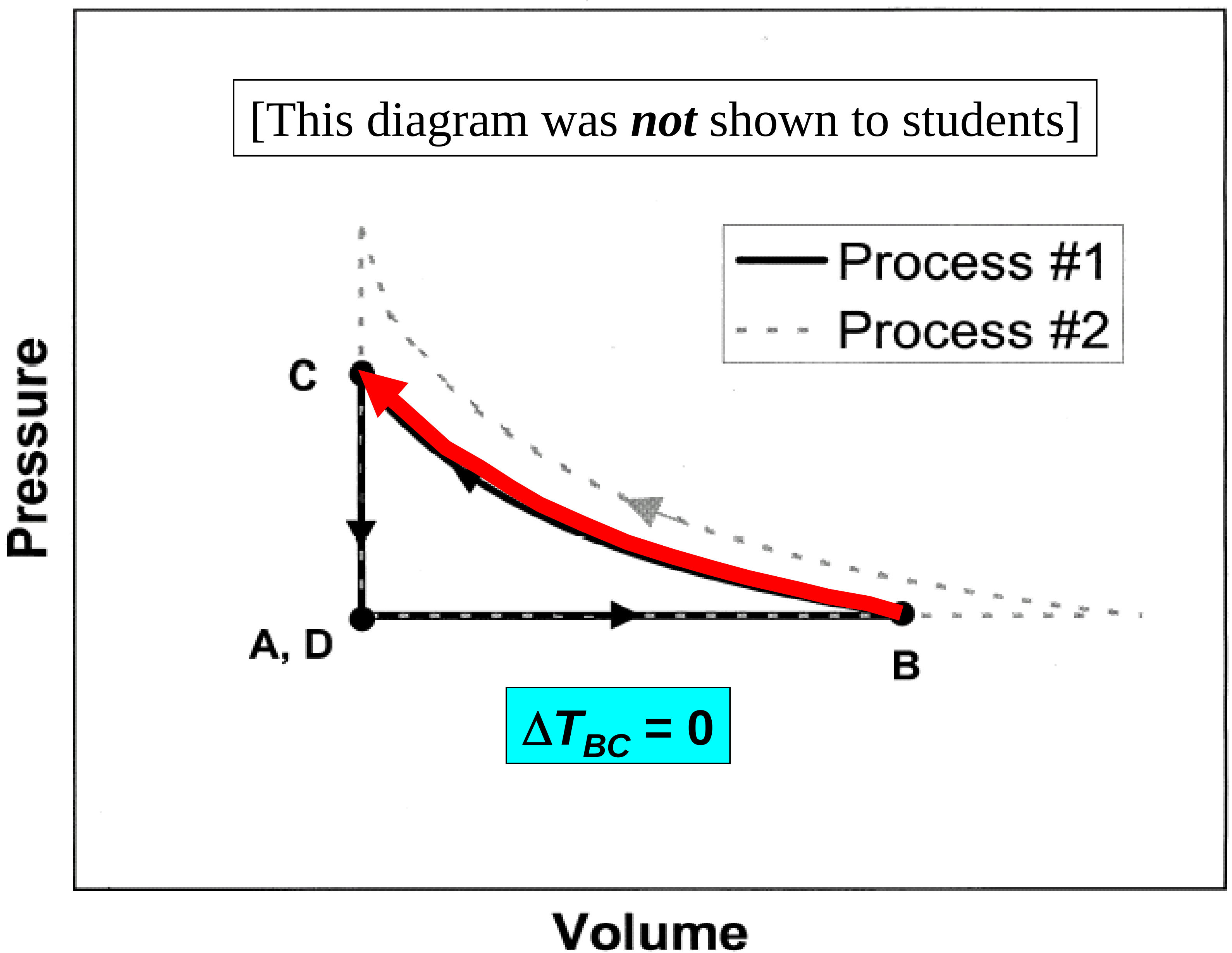
[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
$\Delta T_{BC} = 0$
Pressure
Volume



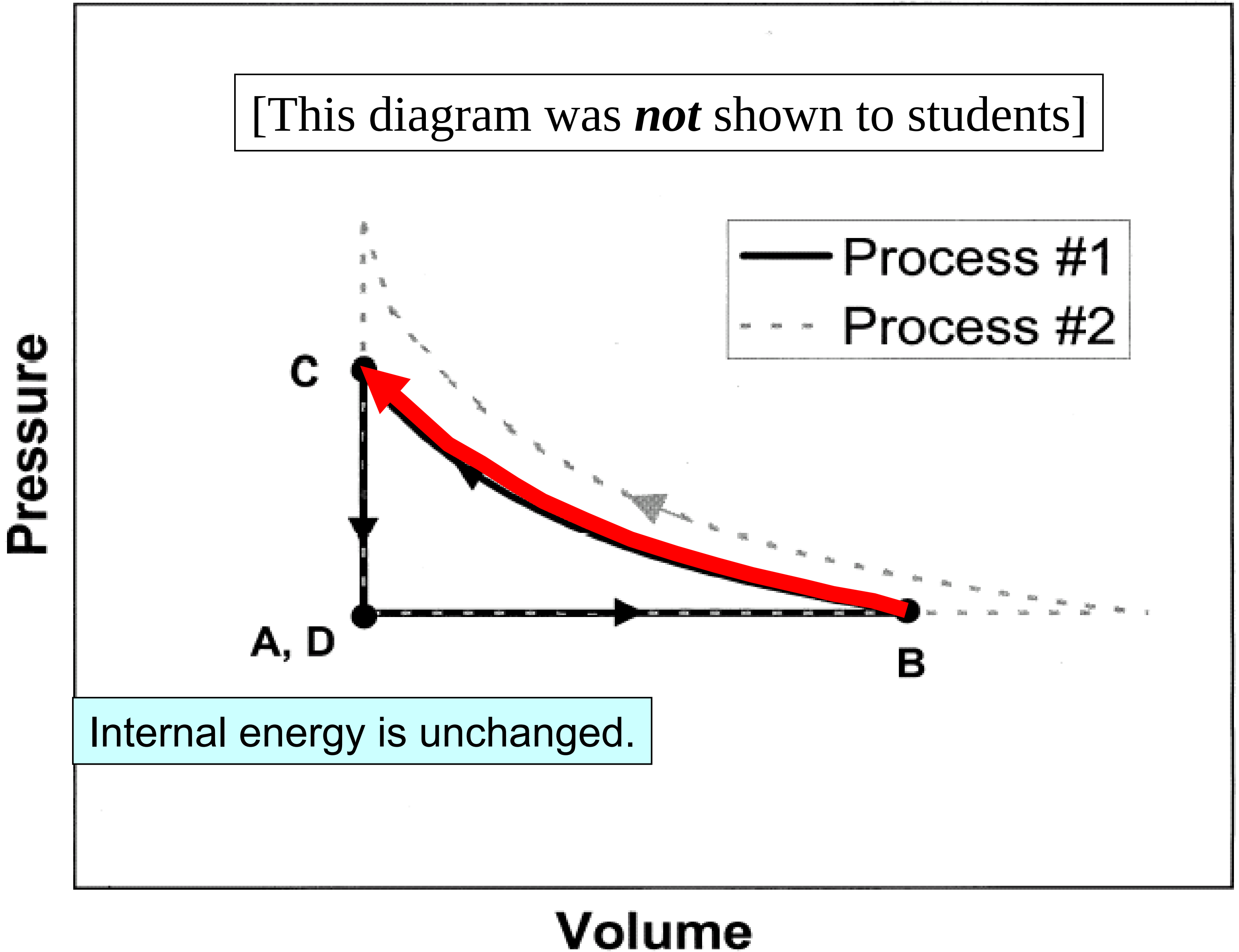
Question #4: During the process that occurs from time *B* to time *C*, is there *any* net energy flow between the gas and the water? If no, explain why not. If yes, is there a net flow of energy from gas to water, or from water to gas?



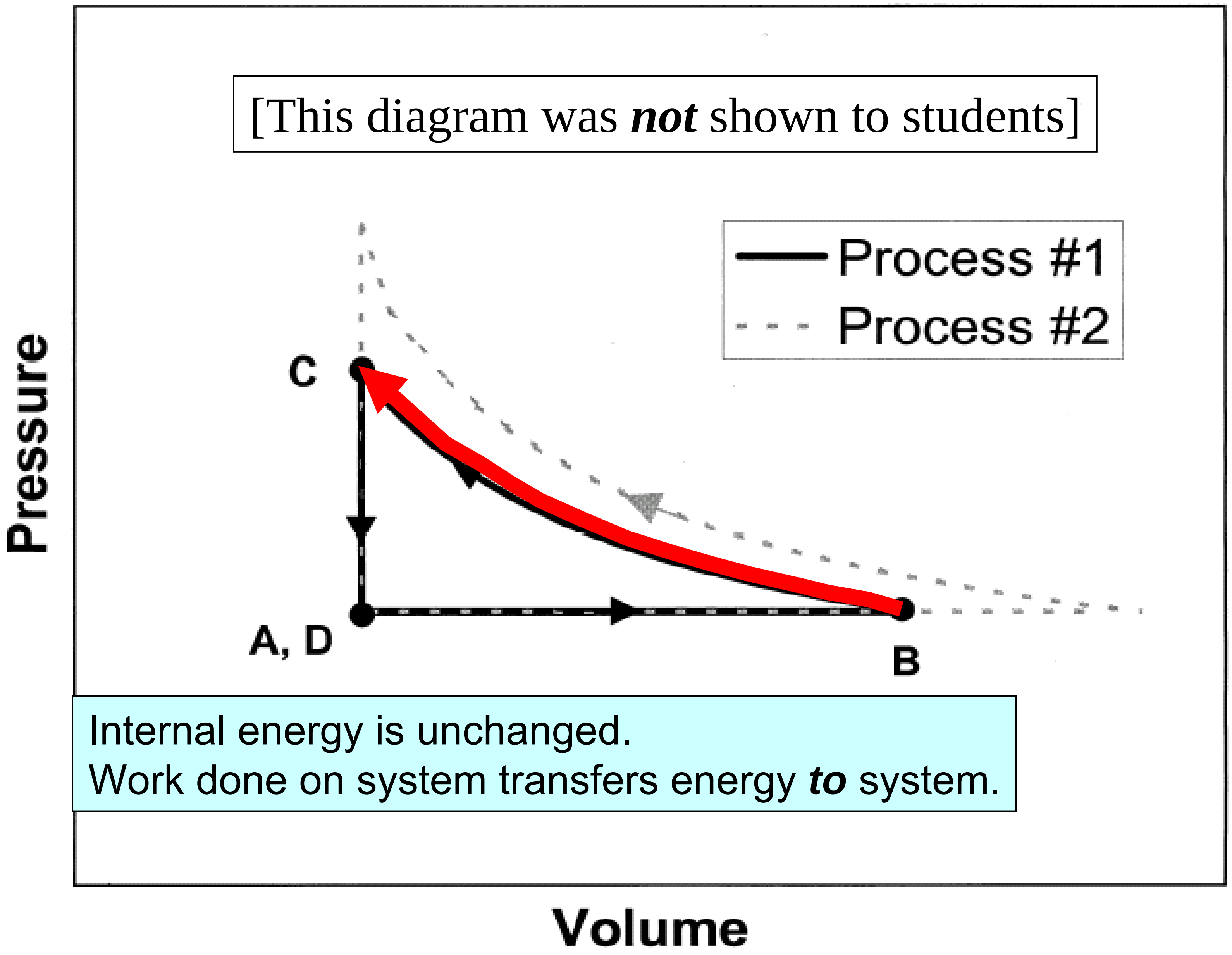
Question #4: During the process that occurs from time *B* to time *C*, is there *any* net energy flow between the gas and the water? If no, explain why not. If yes, is there a net flow of energy from gas to water, or from water to gas?


[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]

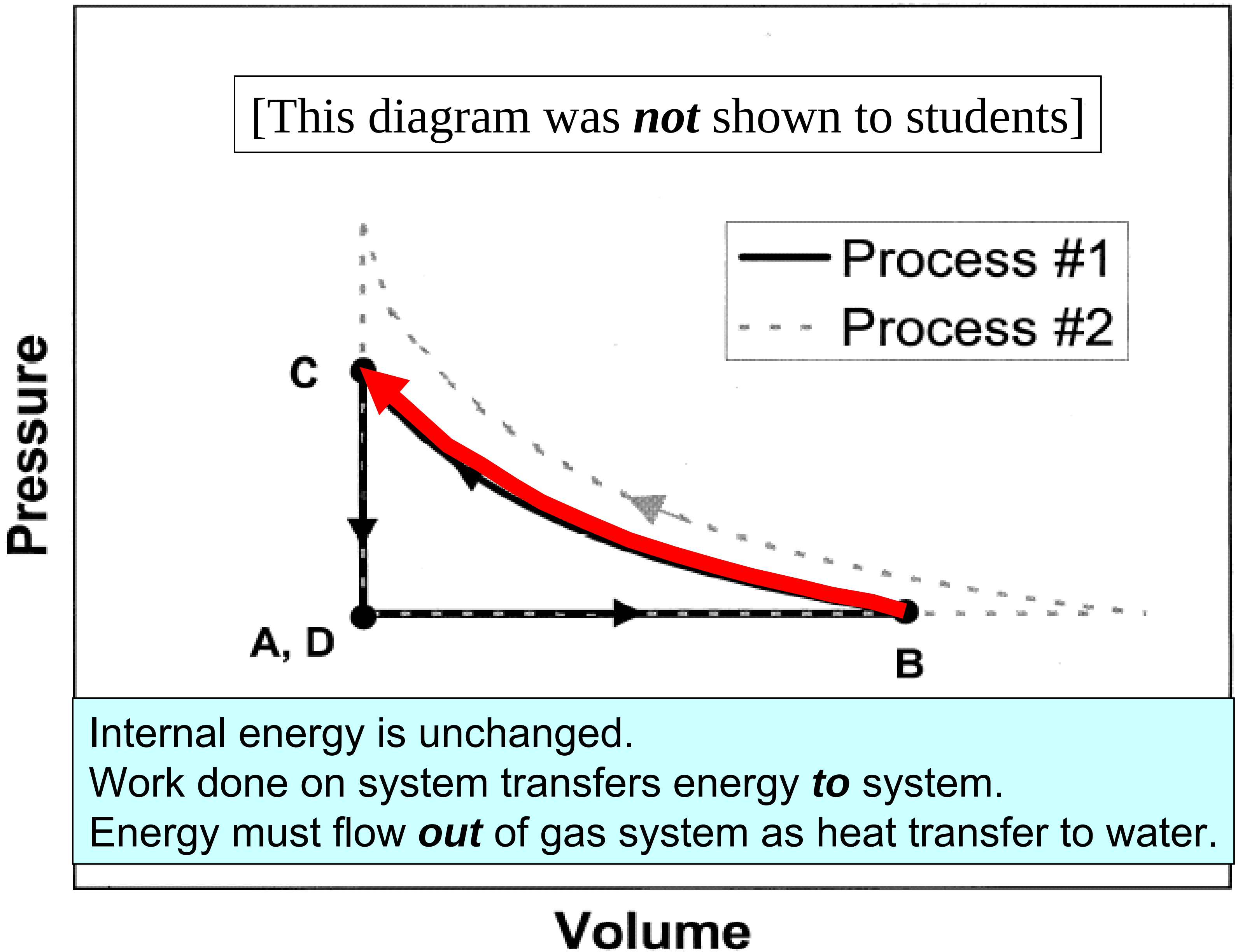


Internal energy is unchanged.

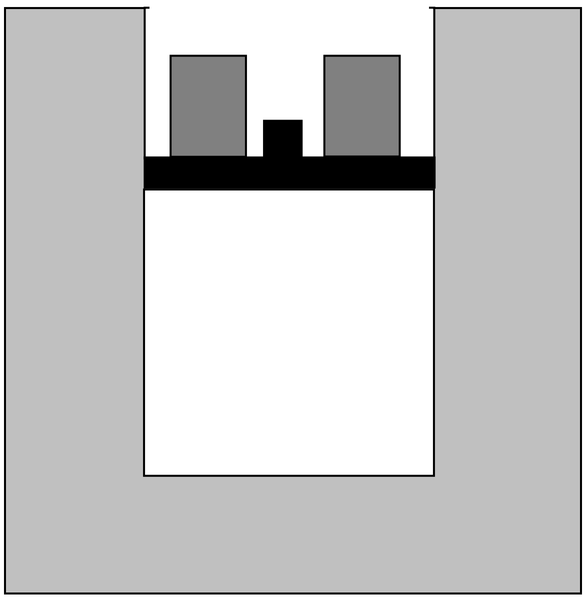


Internal energy is unchanged.
Work done on system transfers energy *to* system.

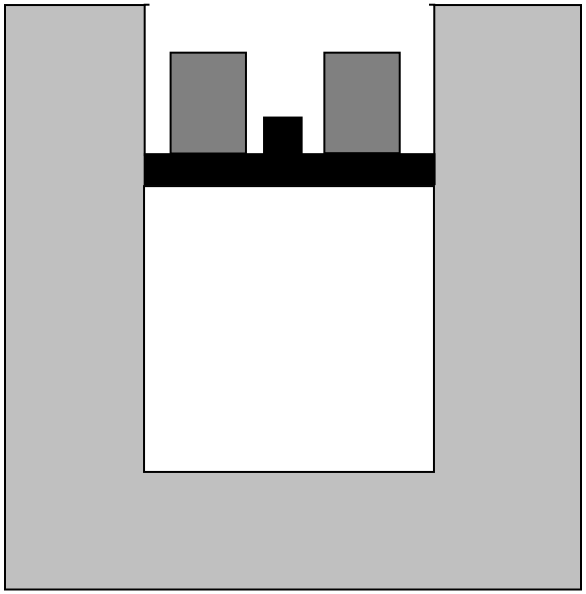
[This diagram was ***not*** shown to students]



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



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



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

Results on 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*."

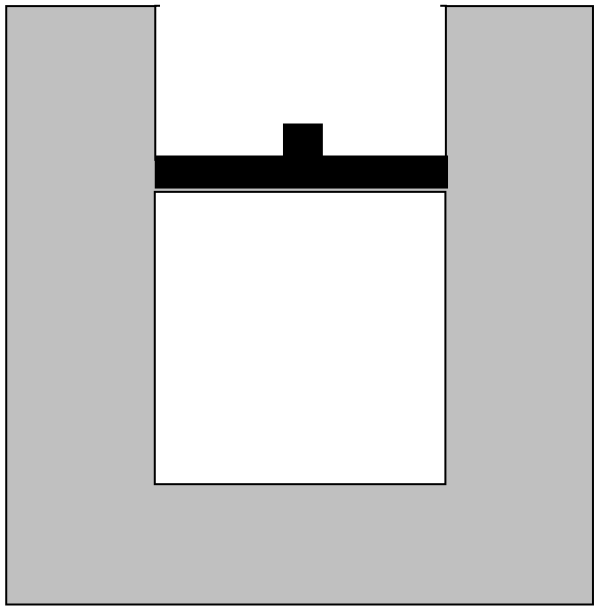
Misunderstanding of "thermal reservoir" concept, in which heat may be transferred to or from an entity that has practically unchanging temperature

Thermal Physics Students Shared Difficulties Manifested by Introductory Students

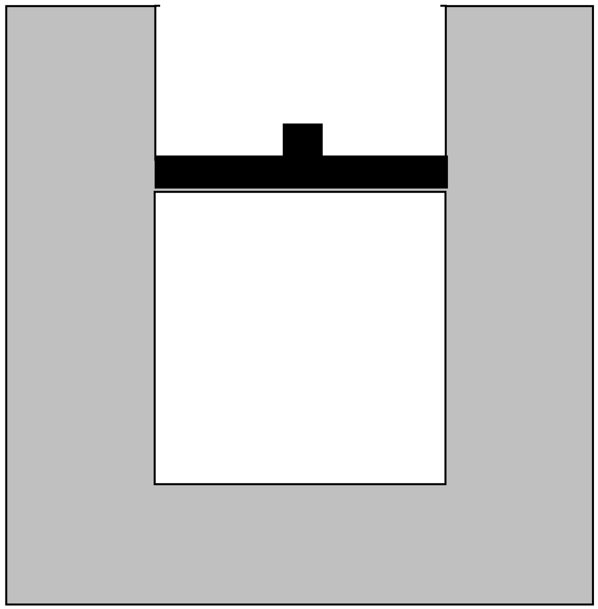
- Failed to recognize that total kinetic energy of ideal gas molecules does ***not*** change when temperature is held constant:
  - **Interview sample: 44%**
  - **2004 Thermal Physics students: 45%**

- Failed to recognize that gas transfers energy to surroundings via work during expansion process:
  - **Interview sample: 59%**
  - **2004 Thermal Physics students: 45%**

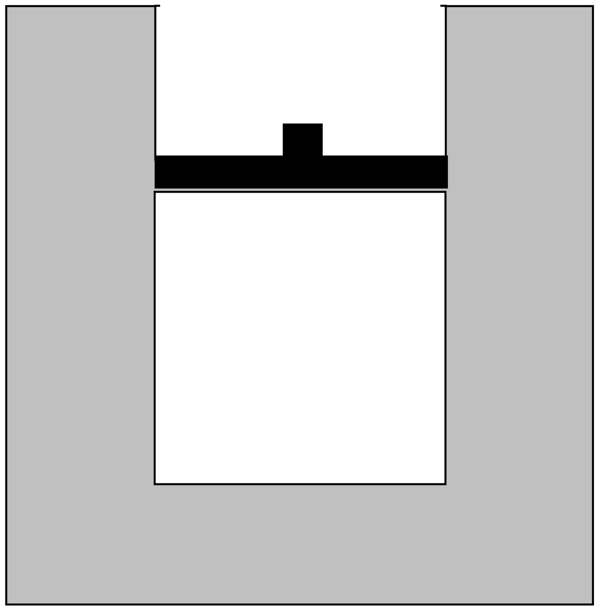
Now, the piston is locked into place so it *cannot move*, and the weights are removed from the piston.



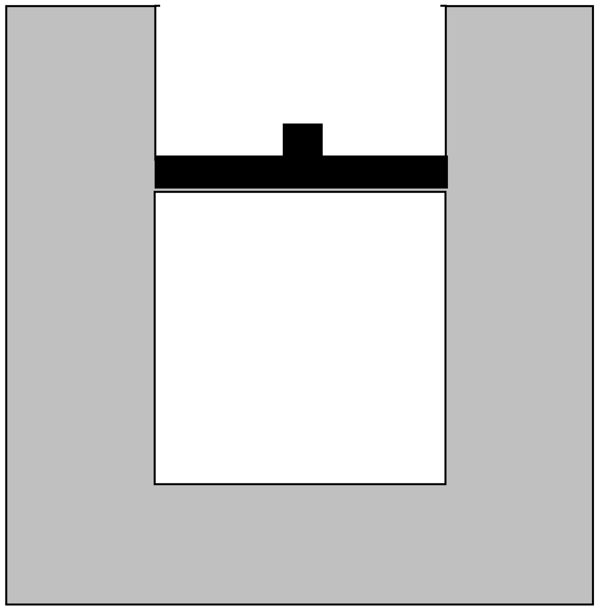
The system is left to sit in the room for many hours.

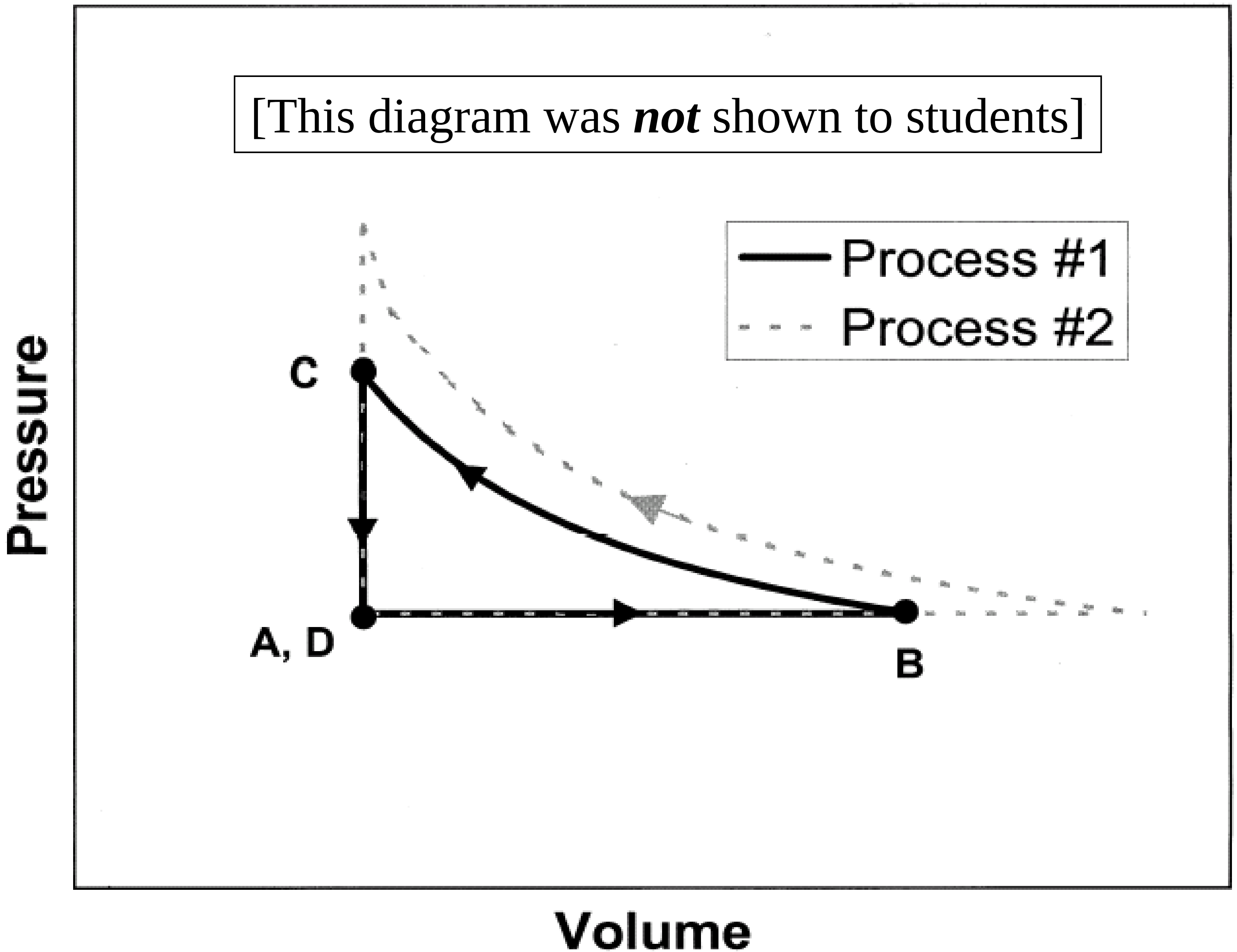


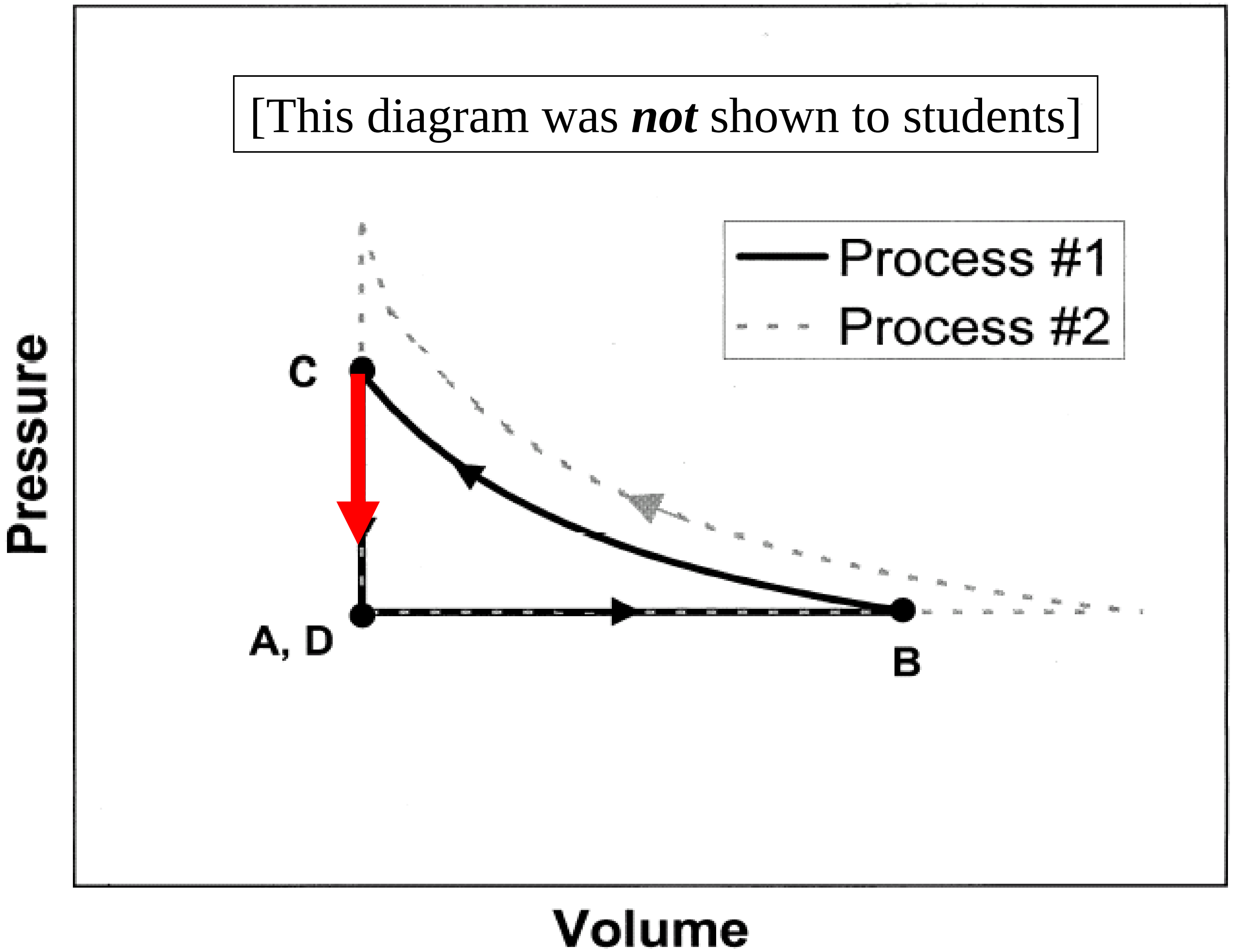
Eventually the entire system cools back down to the same room temperature it had at time ***A.***



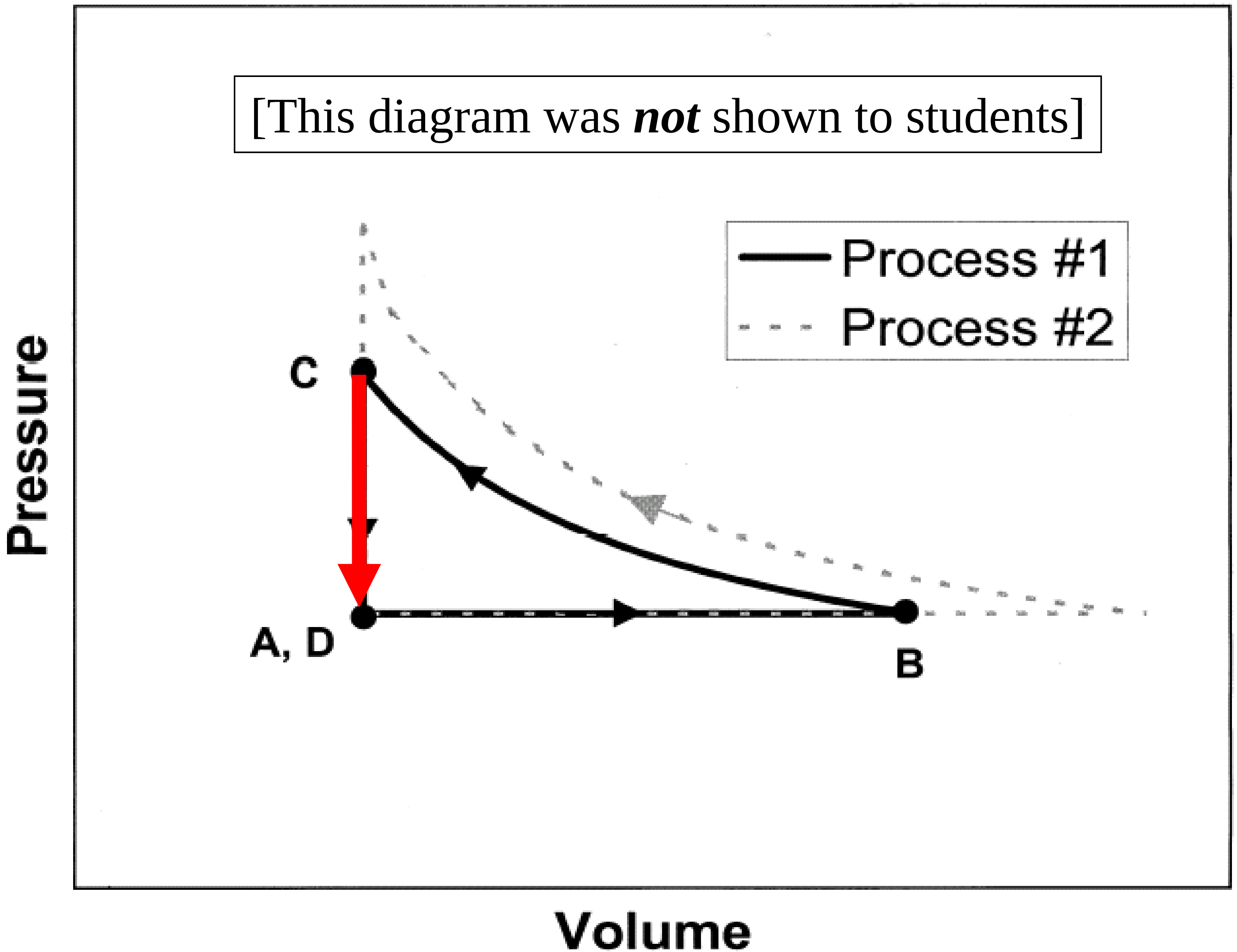
After cooling is complete, it is time ***D.***

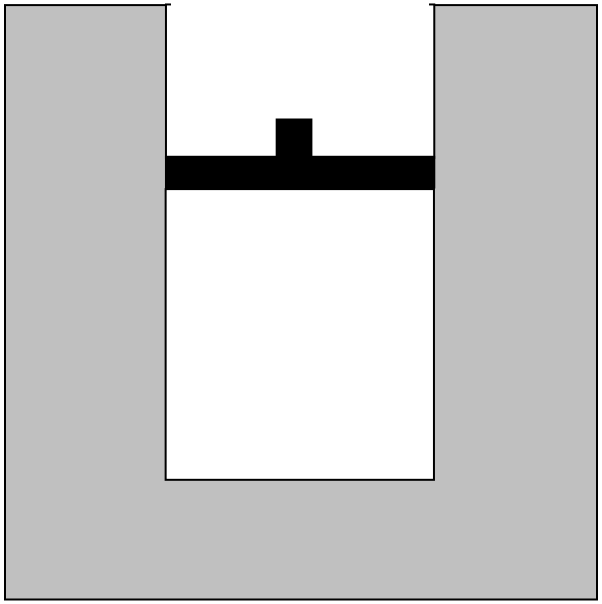



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



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

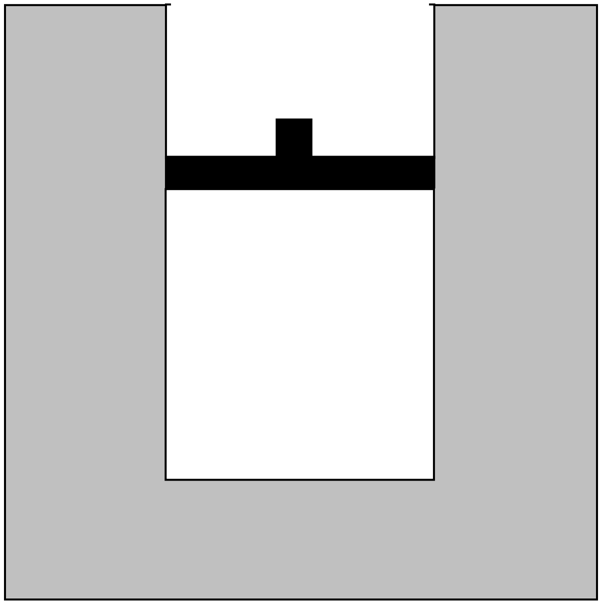

[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



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?

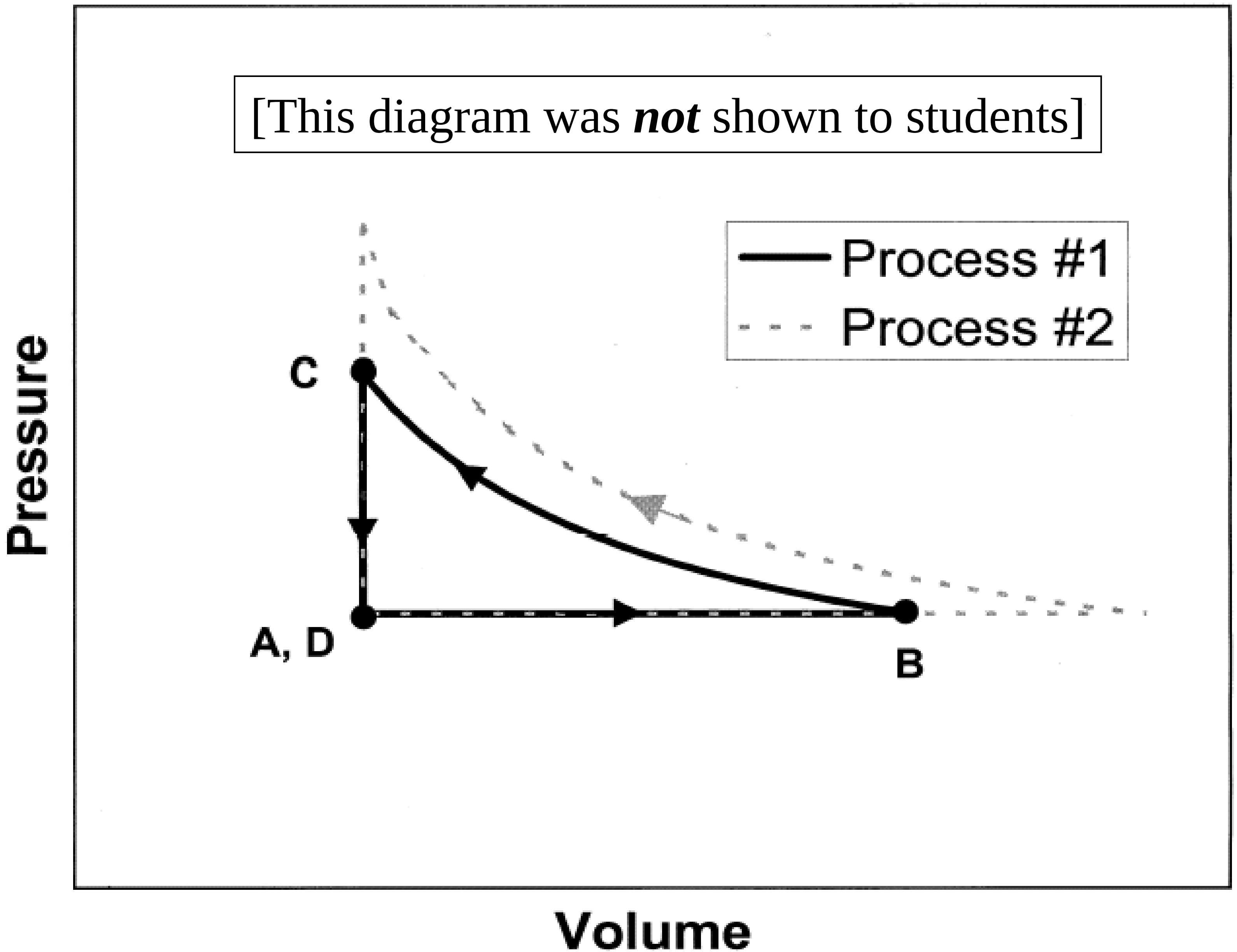
(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

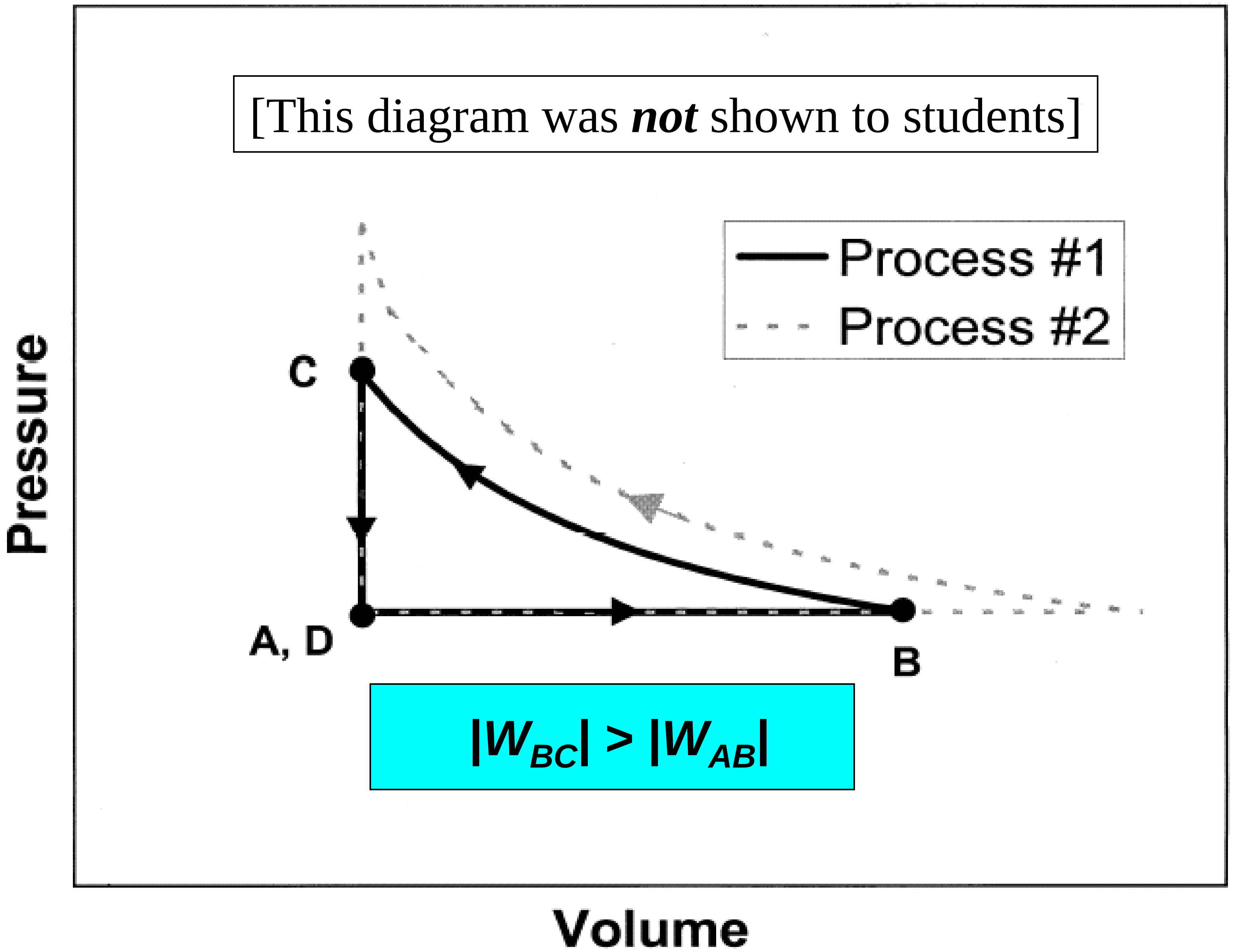


Question #6: Consider ***<u>the entire process</u>*** from time *A* to time *D*.

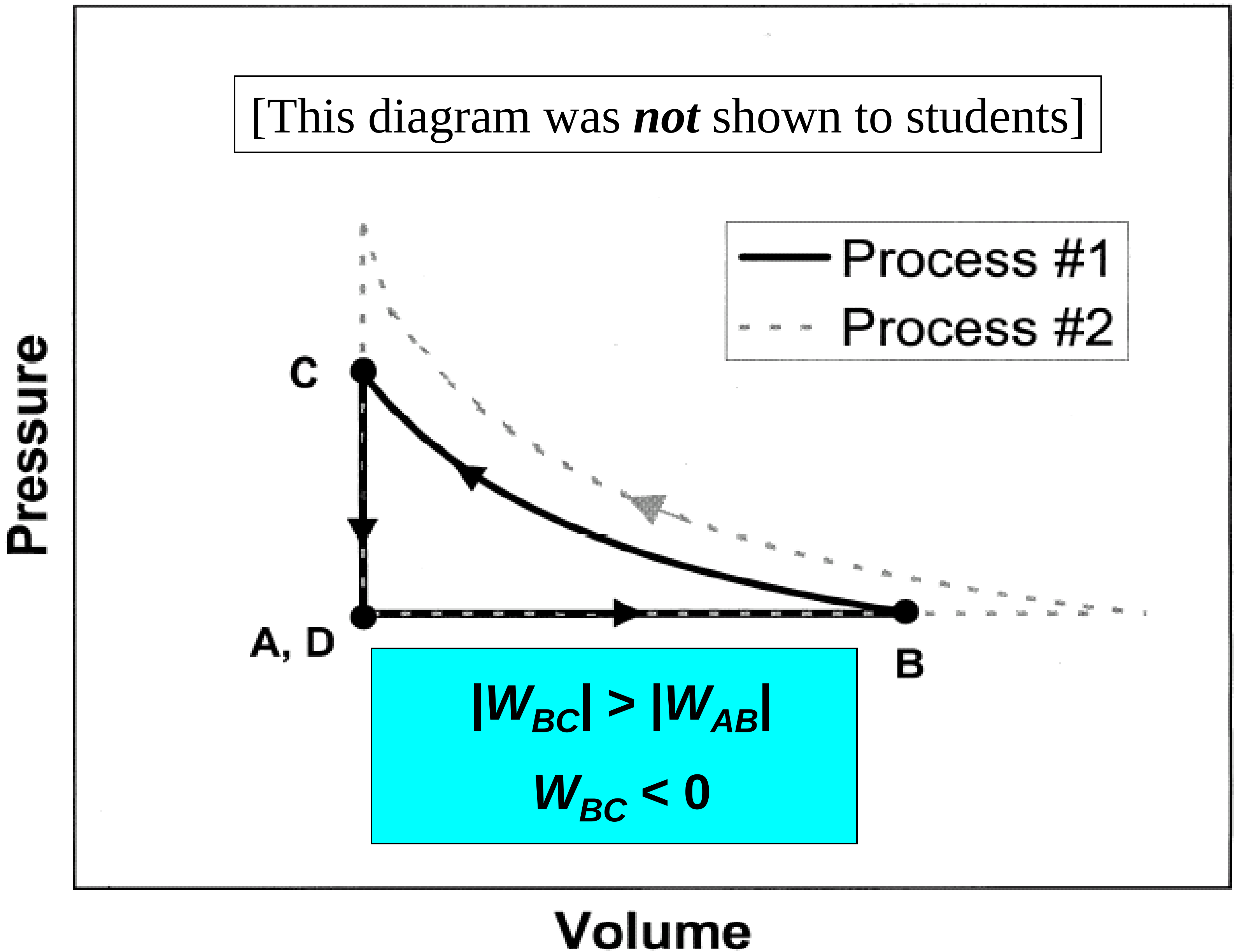
(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

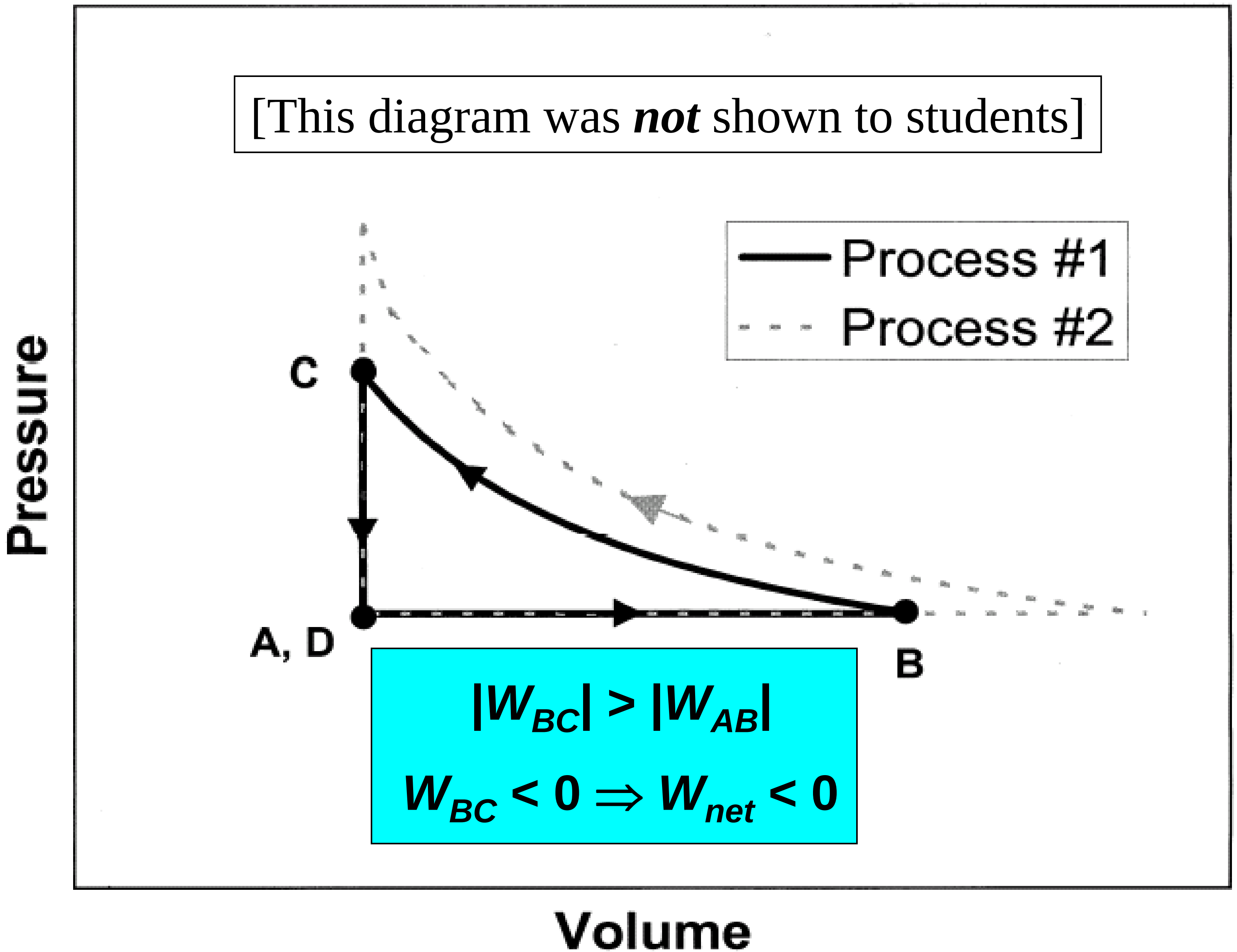
(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

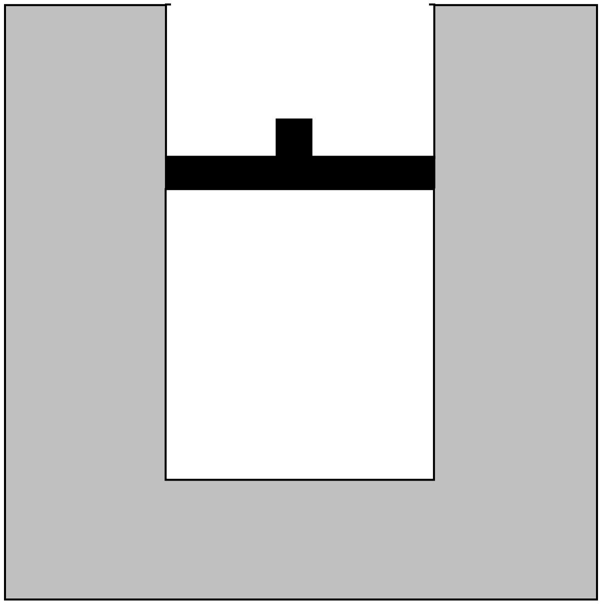

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



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


[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume
|W_BC| > |W_AB|
W_BC < 0

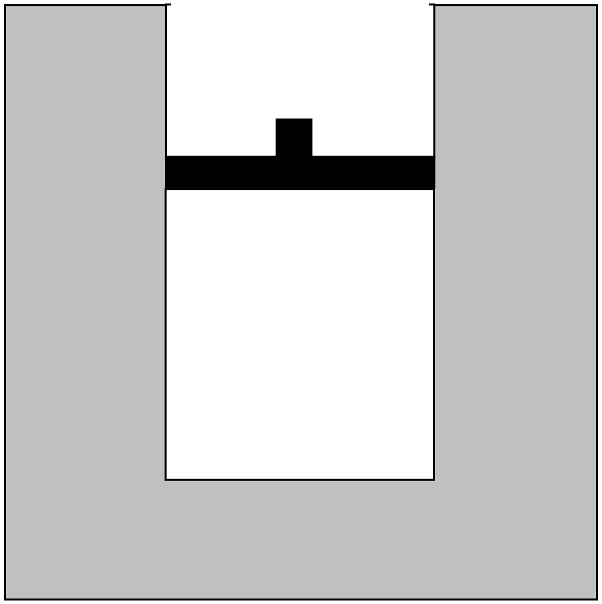

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume
$|W_{BC}| > |W_{AB}|$
$W_{BC} < 0 \Rightarrow W_{net} < 0$



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?



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 (i)

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

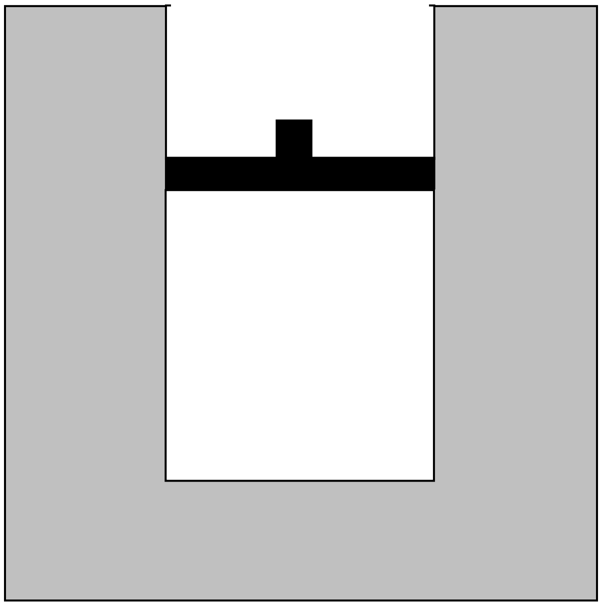
Interview sample *[post-test, N = 32]****: 19%***

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

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

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

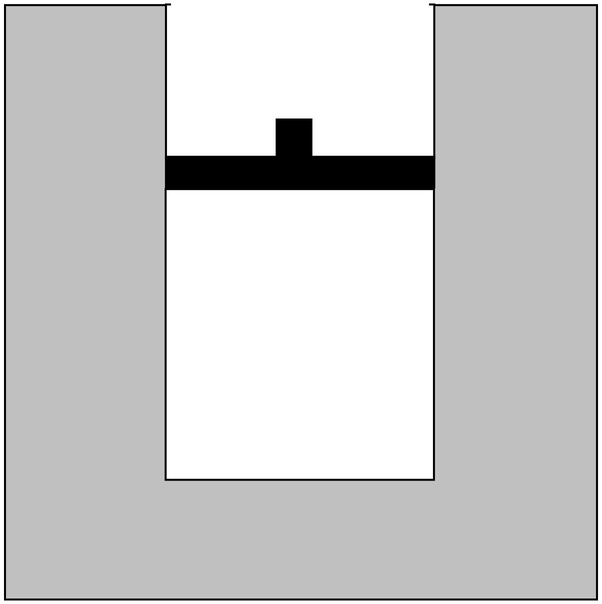
2004 Thermal Physics *[pre-test, N = 16]****: 45%***



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?

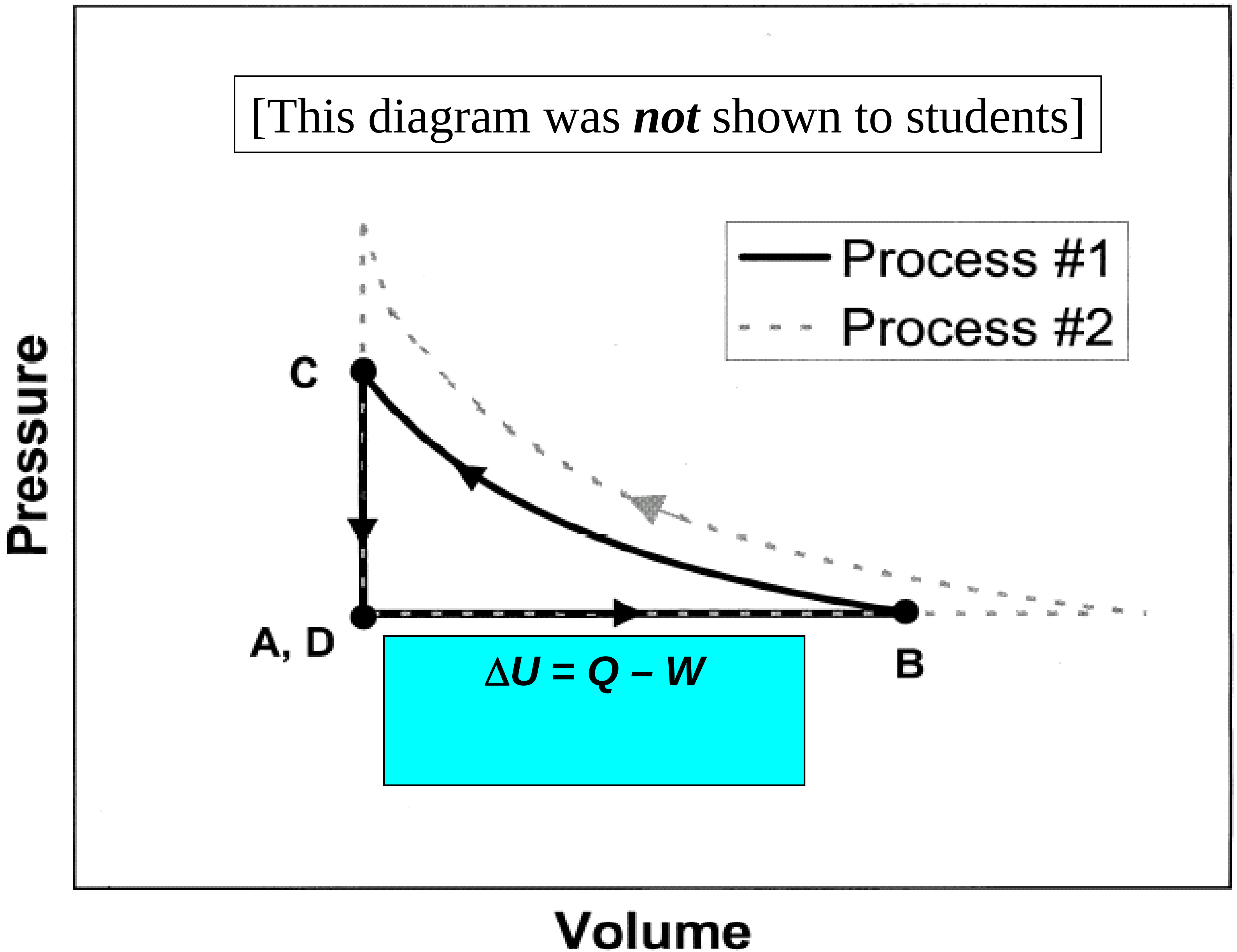
(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?



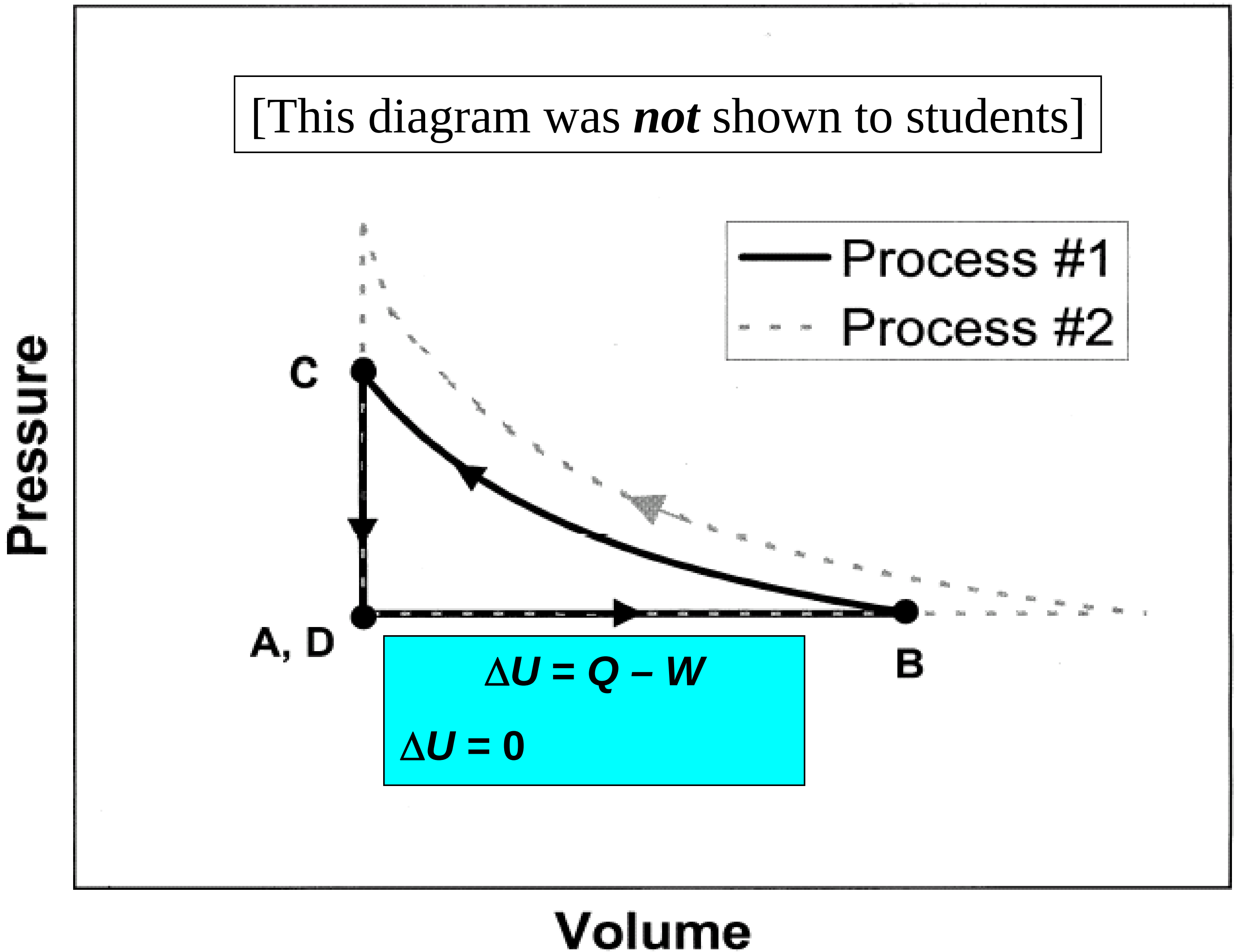
Question #6: Consider ***<u>the entire process</u>*** from time *A* to time *D*.

(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?

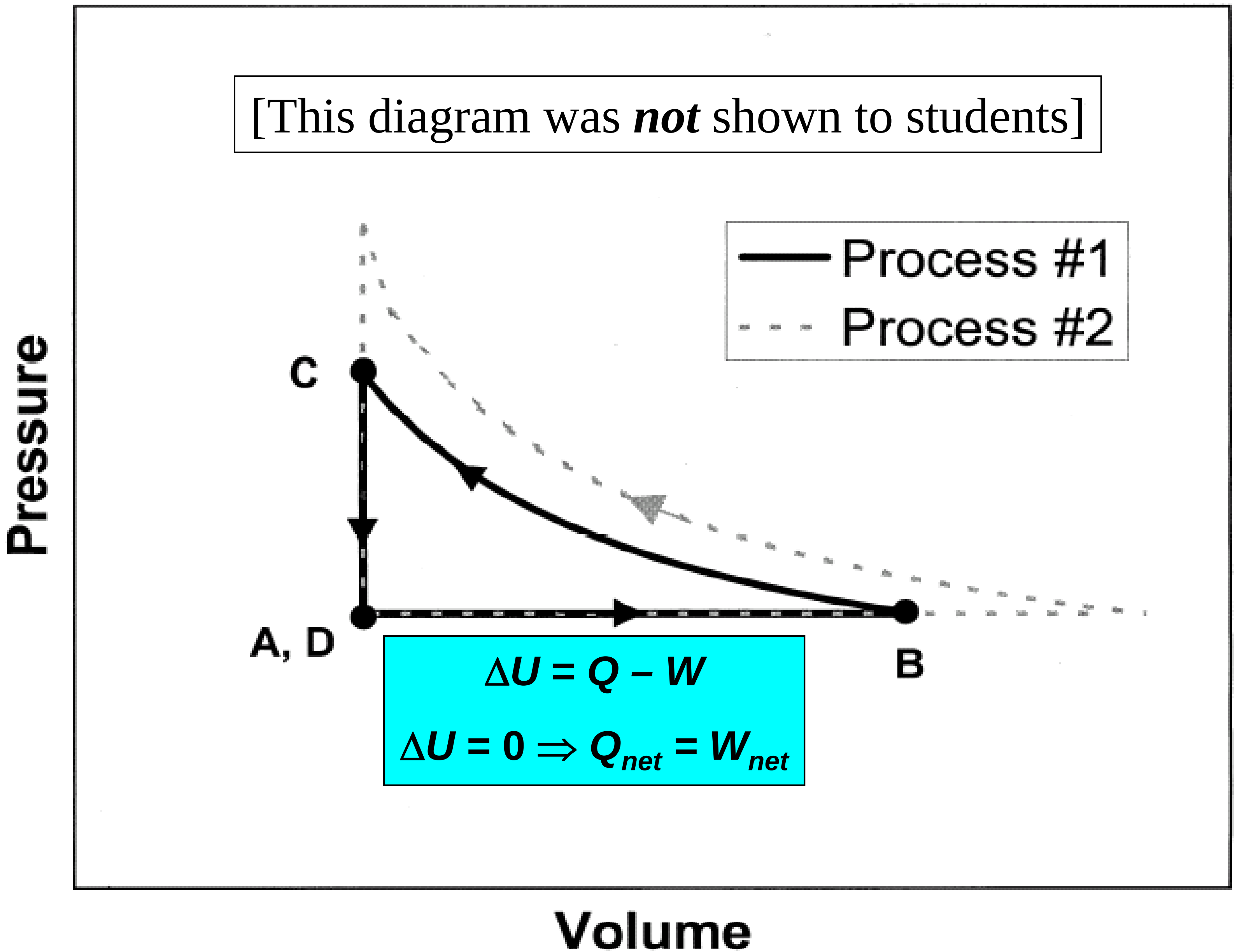


[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
$\Delta U = Q - W$
Pressure
Volume



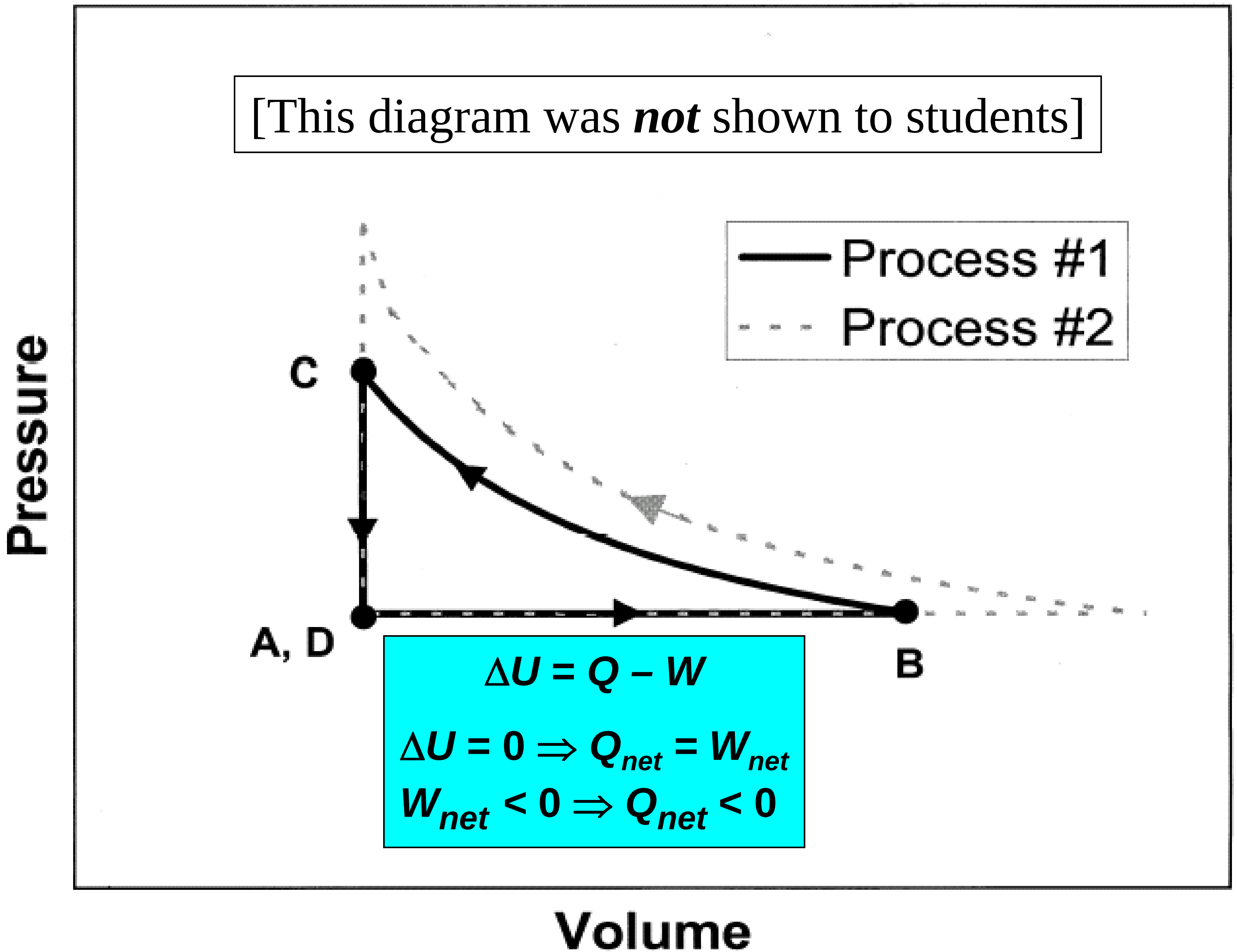
[This diagram was not shown to students]
Process #1
Process #2
Pressure
Volume
C
A, D
B
ΔU = Q – W
ΔU = 0

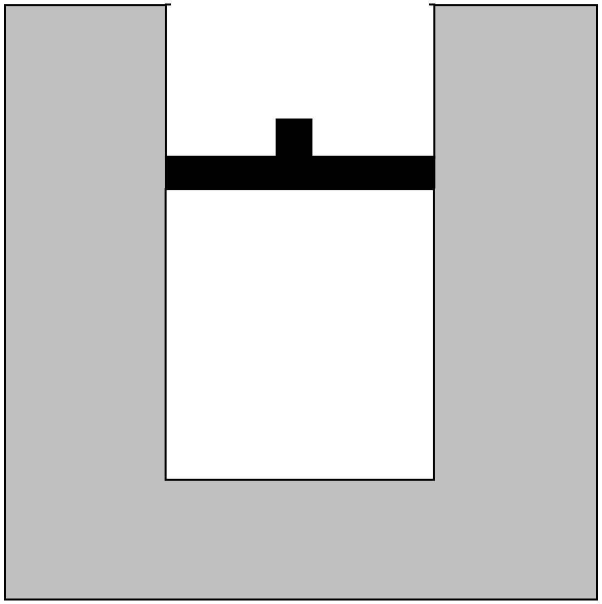
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

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

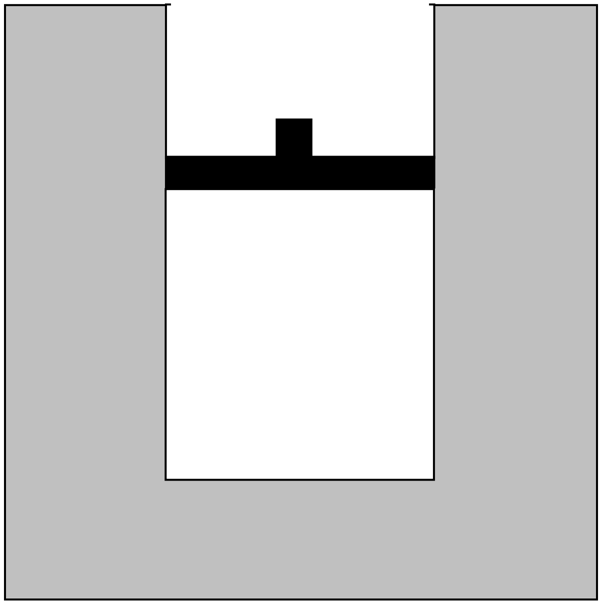

[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume
$\Delta U = Q - W$
$\Delta U = 0 \Rightarrow Q_{net} = W_{net}$
$W_{net} < 0 \Rightarrow Q_{net} < 0$



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?



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 *[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%***

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

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

Virtually identical to results found with introductory students (interview sample)

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

Some Strategies for Instruction

- Focus on meaning of heat as ***transfer*** of energy, ***not*** quantity of energy residing in a system;

Some Strategies for Instruction

- Focus on meaning of heat as ***transfer*** of energy, ***not*** quantity of energy residing in a system;
- Emphasize contrast between heat and work as energy-transfer mechanisms.

Some Strategies for Instruction

Some Strategies for Instruction

- Guide students to make increased use of *PV*-diagrams and similar representations.

Some Strategies for Instruction

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

Some Strategies for Instruction

Some Strategies for Instruction

- Certain common idealizations are very troublesome for many students (e.g., the relation between temperature and kinetic energy of an ideal gas; the meaning of thermal reservoir).

Some Strategies for Instruction

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

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

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.

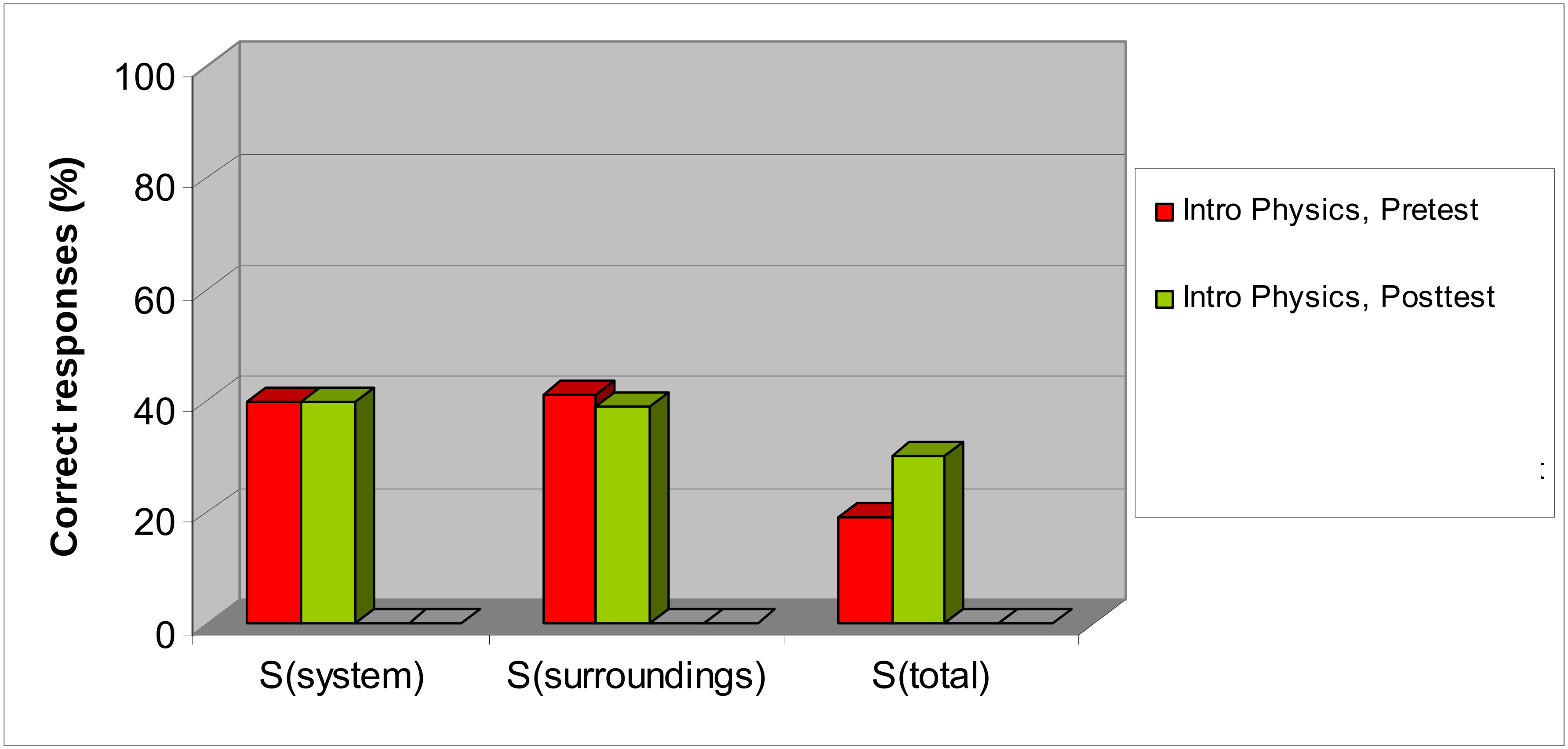
A. During this process, does the entropy of the **<u>system</u>** [S_{system}] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

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

Introductory Students



Less than 40% correct on each question

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*

"Concrete-Context" Question

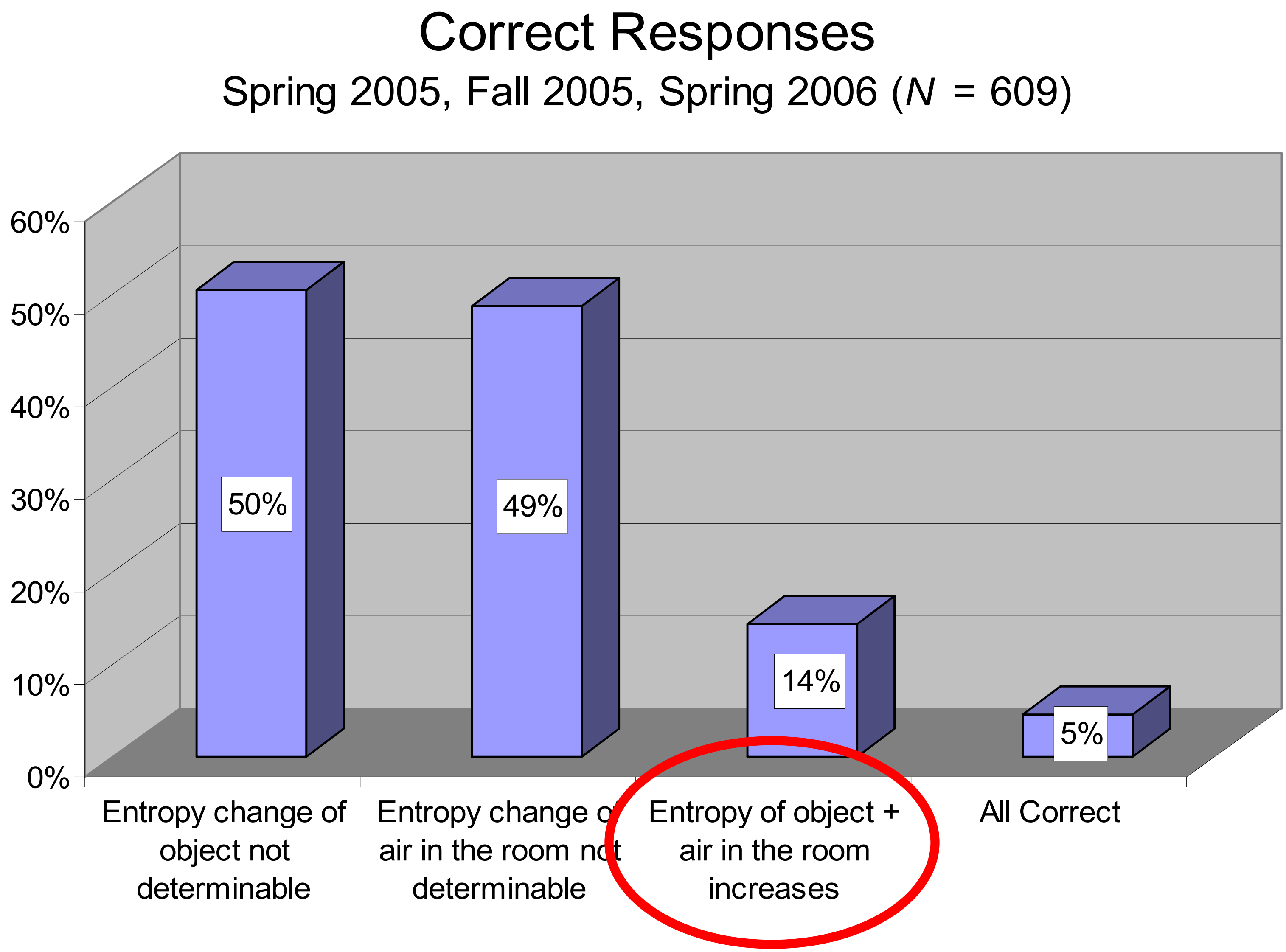
An object is placed in a thermally insulated room that contains air. The object and the air in the room are initially at different temperatures. The object and the air in the room are allowed to exchange energy with each other, but the air in the room does not exchange energy with the rest of the world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

Pre-instruction Data



“Total entropy” responses

- Nearly three-quarters 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

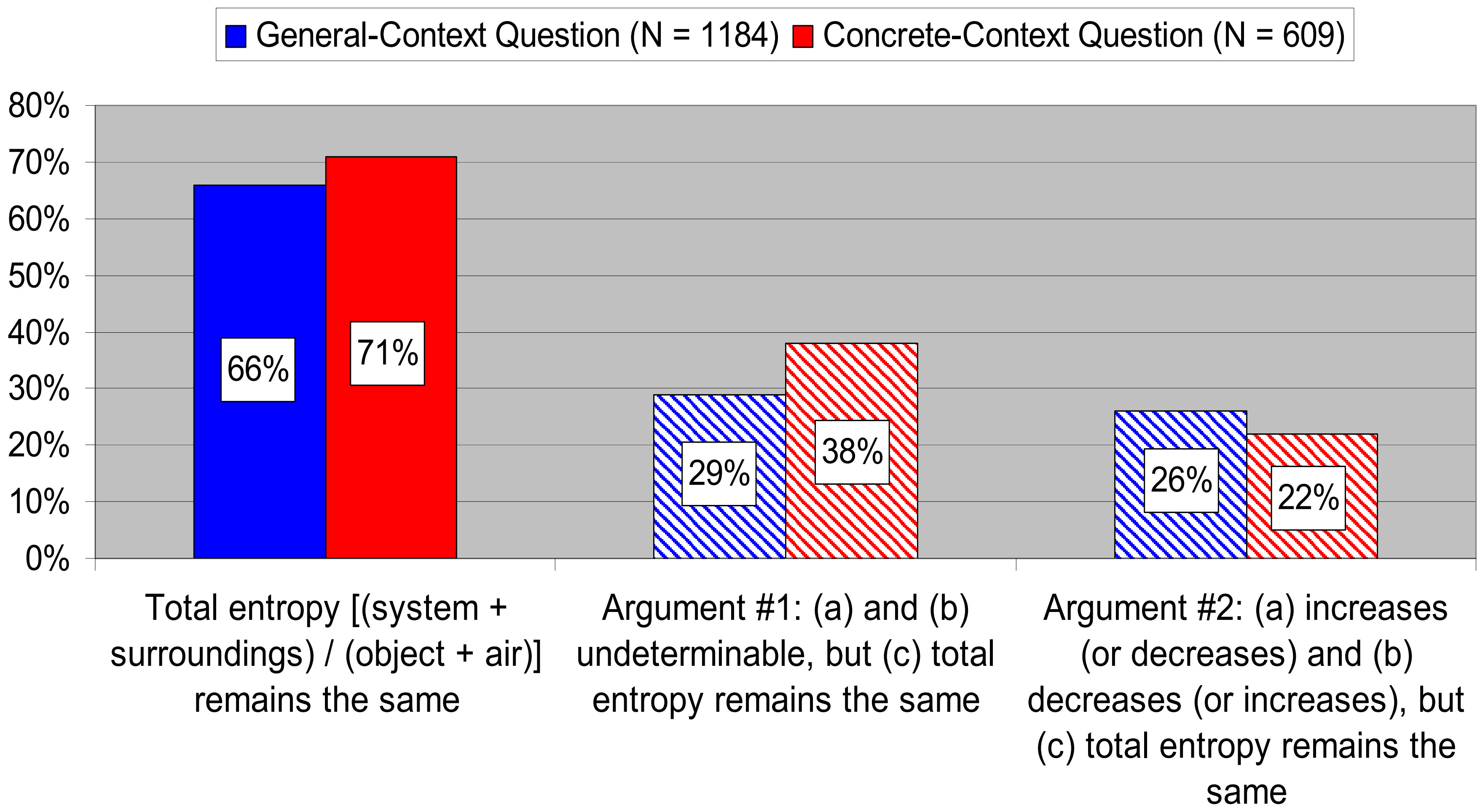
Conservation Argument #1

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

Conservation Argument #2

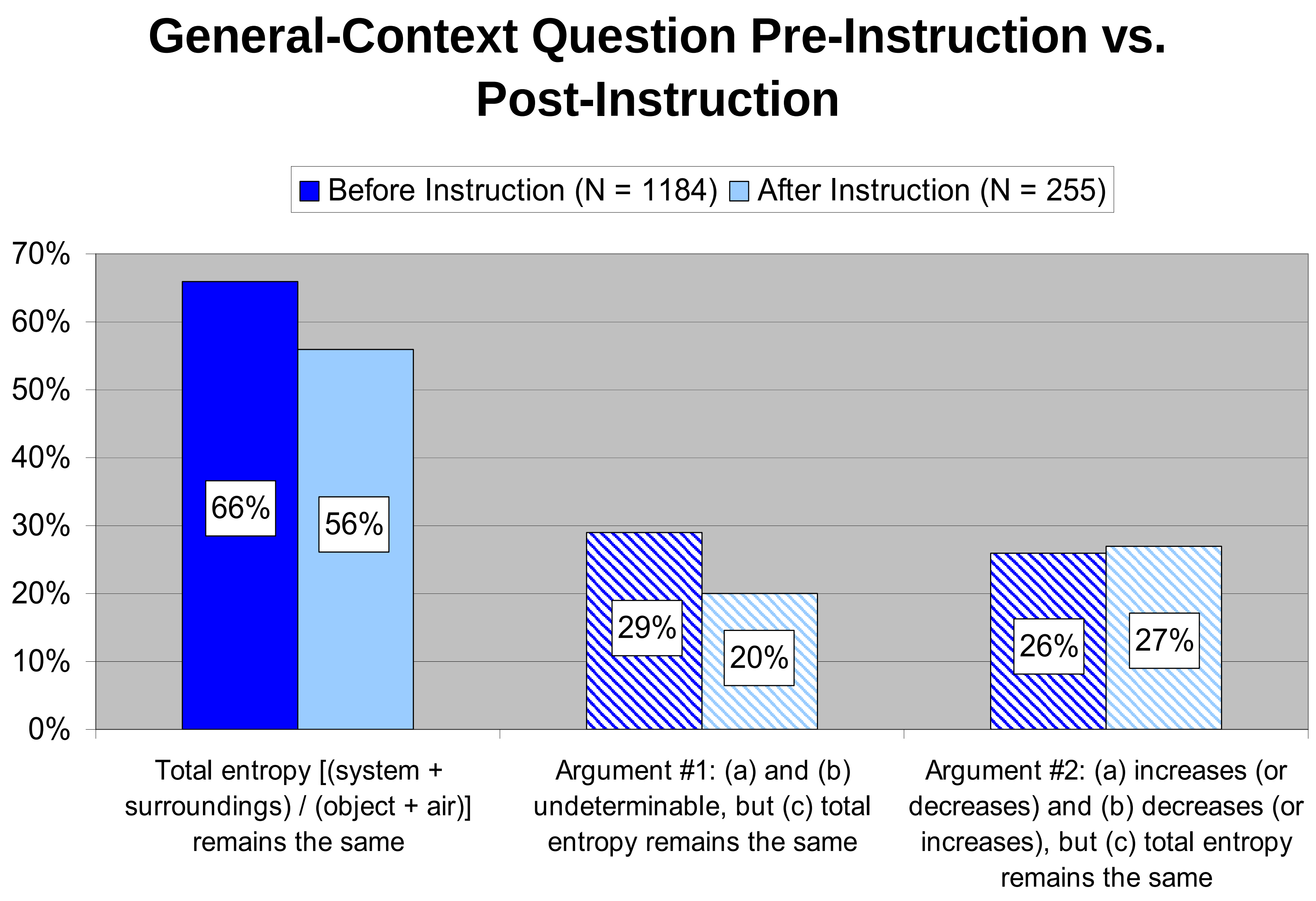
S_{System} increases [*decreases*],
$S_{\text{Surroundings}}$ decreases [*increases*], and
$S_{\text{System}} + S_{\text{Surroundings}}$ stays the same

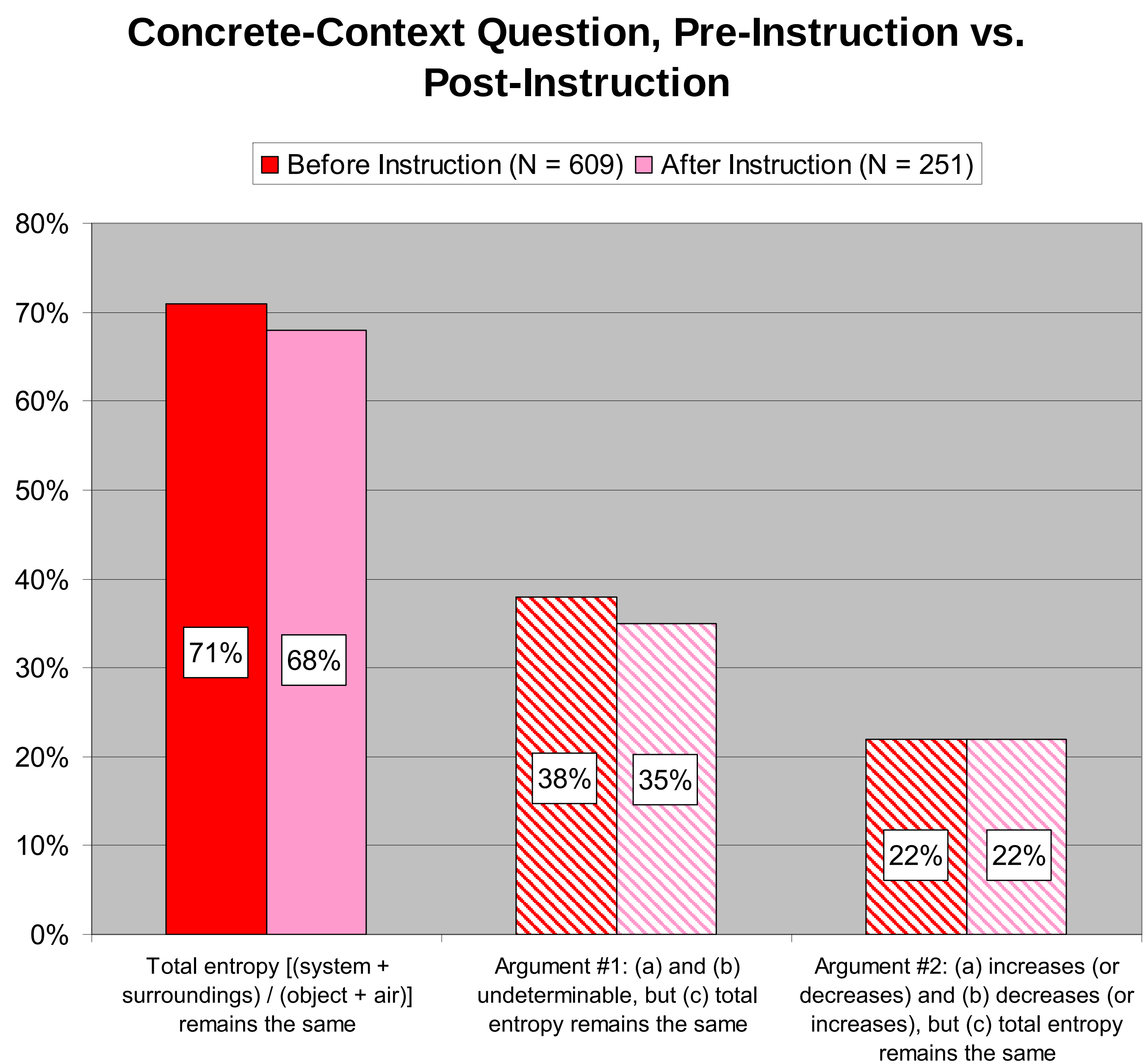
Pre-Instruction Responses Consistent with Entropy "Conservation"



Pre- vs. Post-instruction

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


General-Context Question Pre-Instruction vs. Post-Instruction
Before Instruction (N = 1184)
After Instruction (N = 255)
70%
60%
50%
40%
30%
20%
10%
0%
66%
56%
29%
20%
26%
27%
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



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

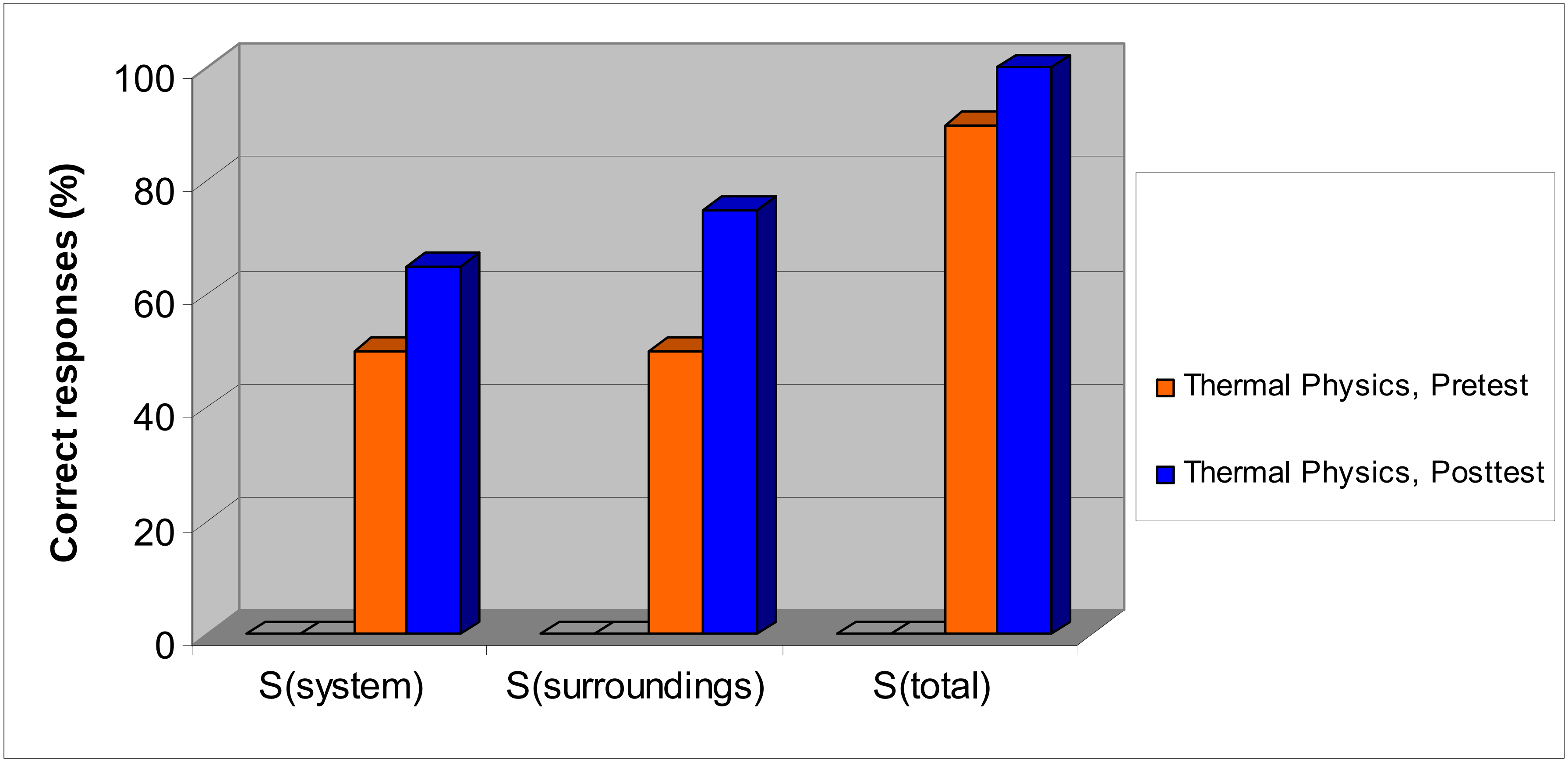
Both before and after instruction…

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

Responses to General-Context Question

Advanced Students



Thermal Physics Posttest: Interactive Engagement, no focused tutorial

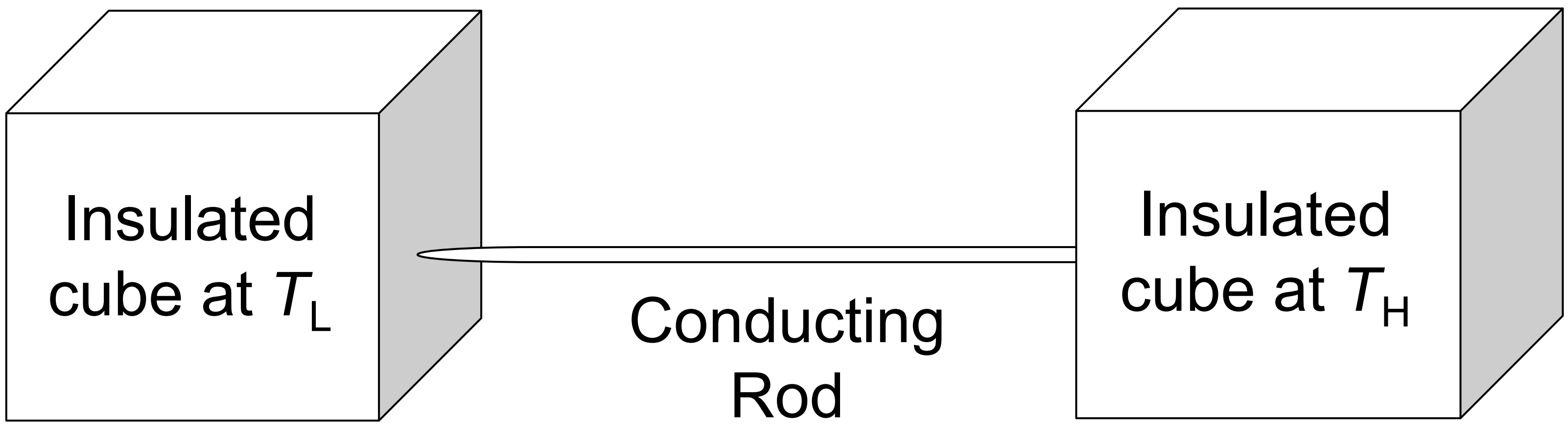
Thermal Physics Students' Thinking on Spontaneous Processes

- Readily accept that "entropy of system ***plus*** surroundings increases"
  - in contrast to introductory students

- Tendency to assume that "system entropy" must *always* increase
  - similar to thinking of introductory students

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…

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 cubes] *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

Preliminary results are promising…

Entropy Tutorial

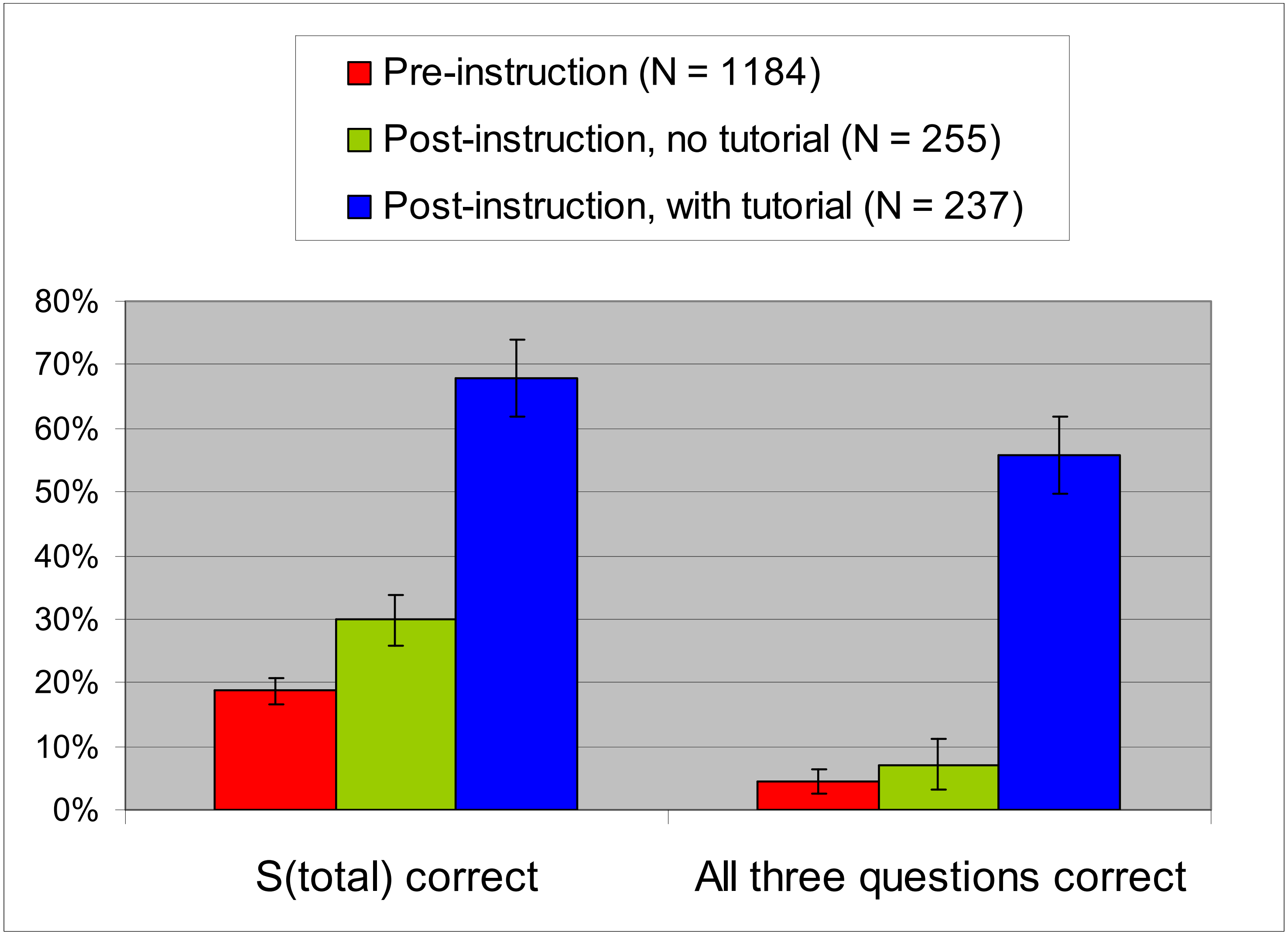
(draft by W. Christensen and DEM, undergoing class testing)

- Guide students to find that:

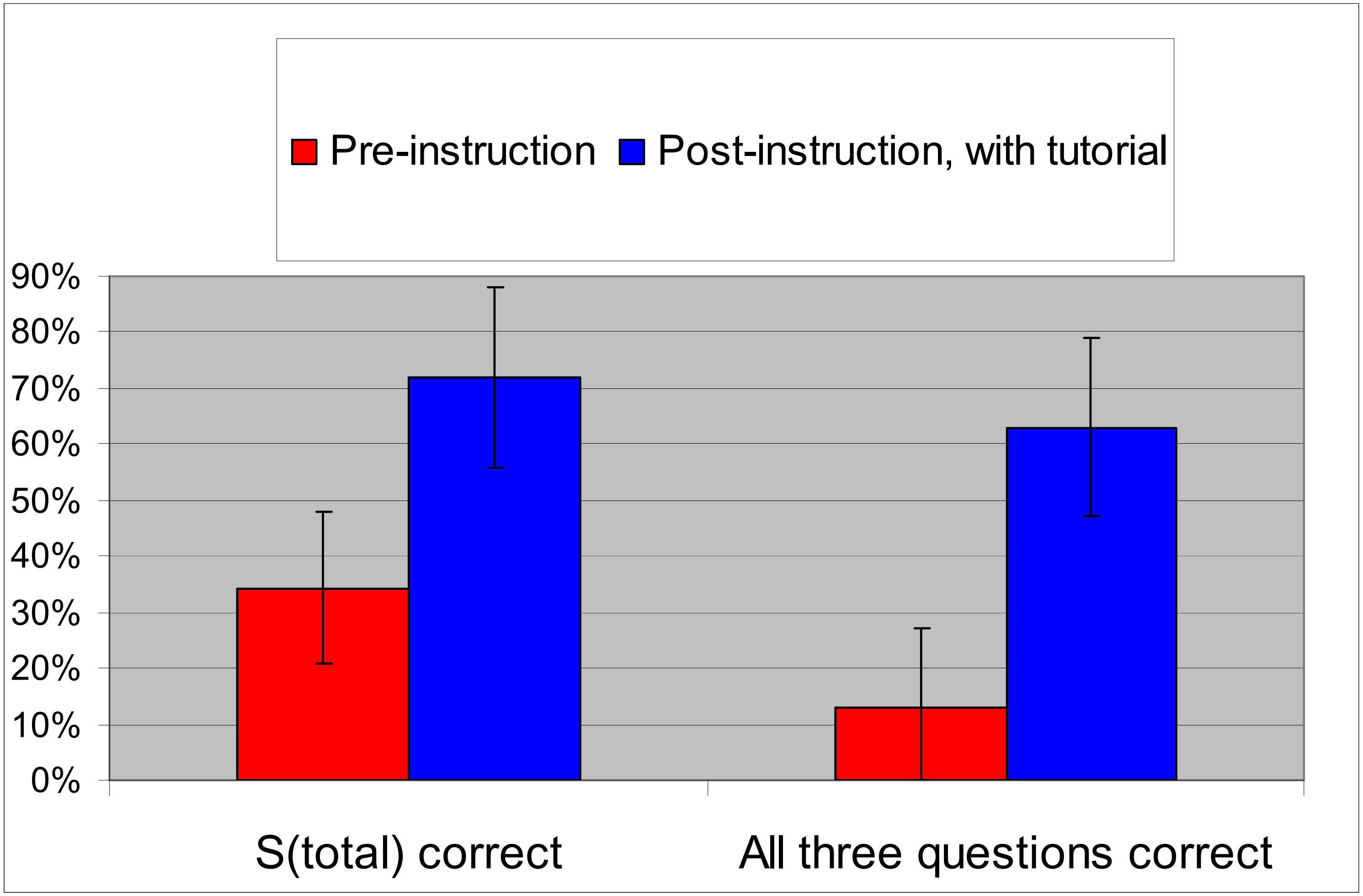
  and that definitions of “system” and “surroundings” are arbitrary

Preliminary results are promising…

Responses to General-Context Question
Introductory Students



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



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.