Detecting and Addressing Students' Reasoning Difficulties in Thermal Physics

David E. Meltzer

Department of Physics
University of Washington
Seattle, Washington, USA

Supported in part by U.S. National Science Foundation
Grant Nos. DUE 9981140, PHY 0406724, and PHY 0604703

Collaborators

- Tom Greenbowe (ISU Chemistry)
- John Thompson (U. Maine Physics)

Students

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

Funding

- NSF Division of Undergraduate Education
- NSF Division of Physics

Research on the Teaching and Learning of Thermal Physics

- Investigate student learning of statistical thermodynamics
- Probe evolution of students' thinking from introductory through advanced-level course
- Develop research-based curricular materials

In collaboration with John Thompson, University of Maine

Background

- Research on learning of thermal physics in introductory courses:
  - 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)
  - calculus-based introductory physics (DEM, *Am. J. Phys*. **72**, 1432, 2004; 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 in general physics courses have revealed substantial 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).

Germany

R. Berger and H. Wiesner (1997)

France

S. Rozier and L. Viennot (1991)

UK

J. W. Warren (1972)

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 ≥ 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

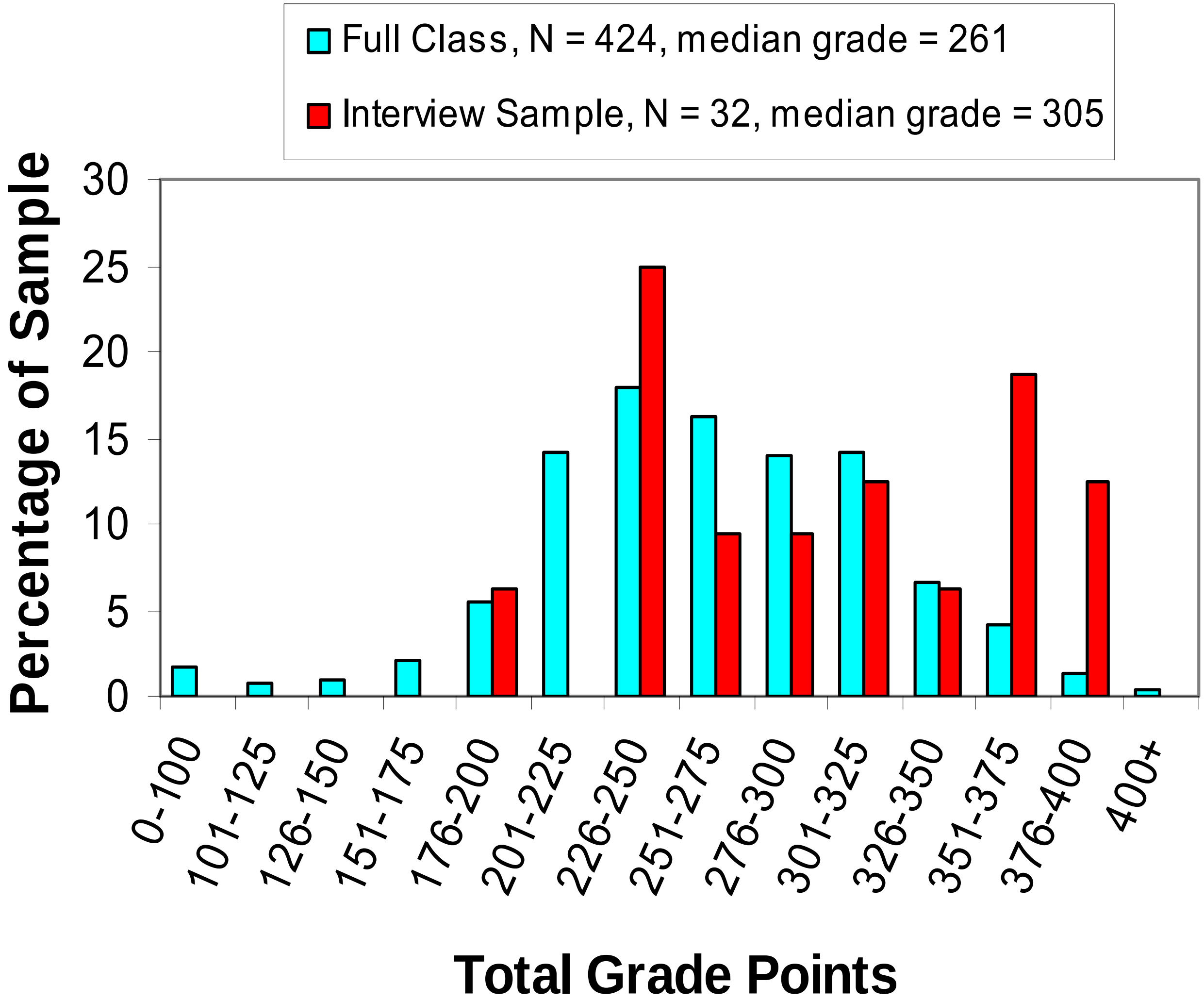
Performance Comparison: Upper-level vs. Introductory Students

- 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

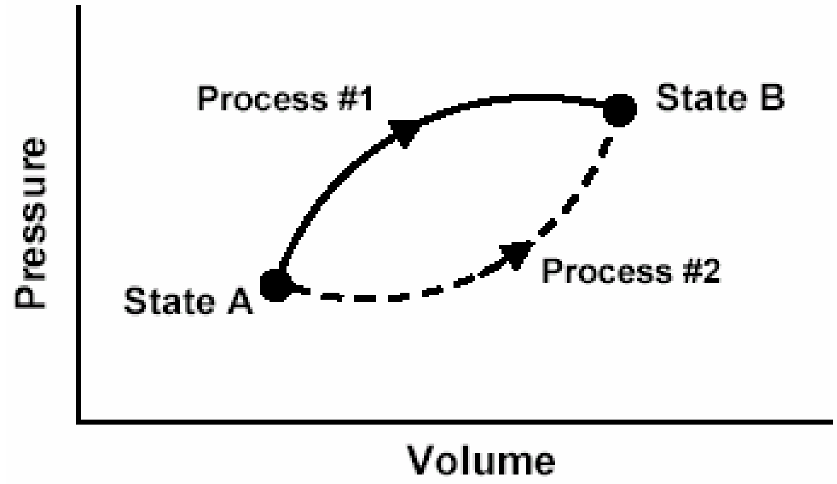
Grade Distributions: Interview Sample vs. Full Class



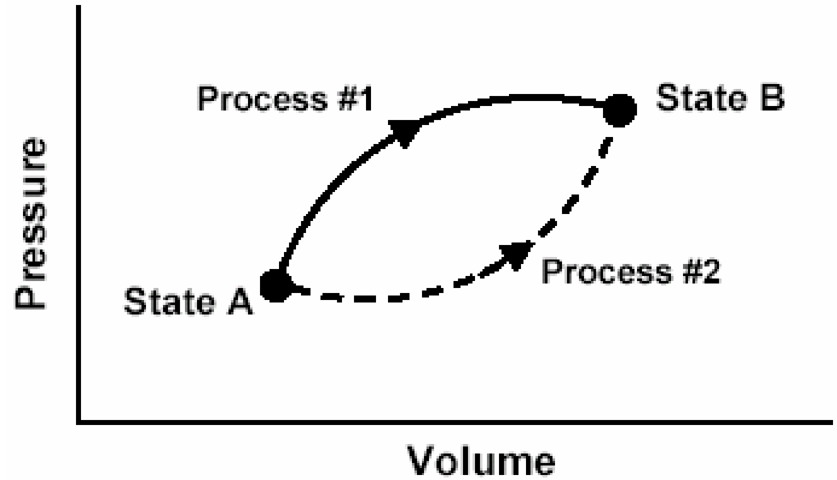
***Interview Sample*:**

34% above 91^{st} percentile; 50% above 81^{st} 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:

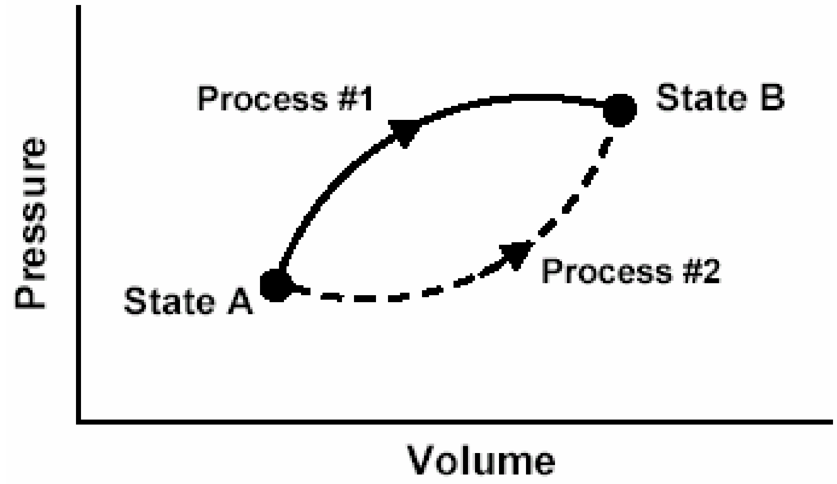


[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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:



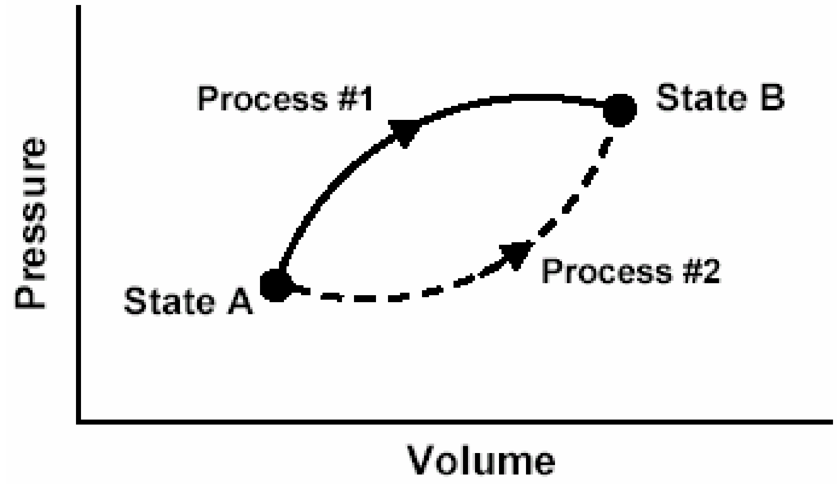
[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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:

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



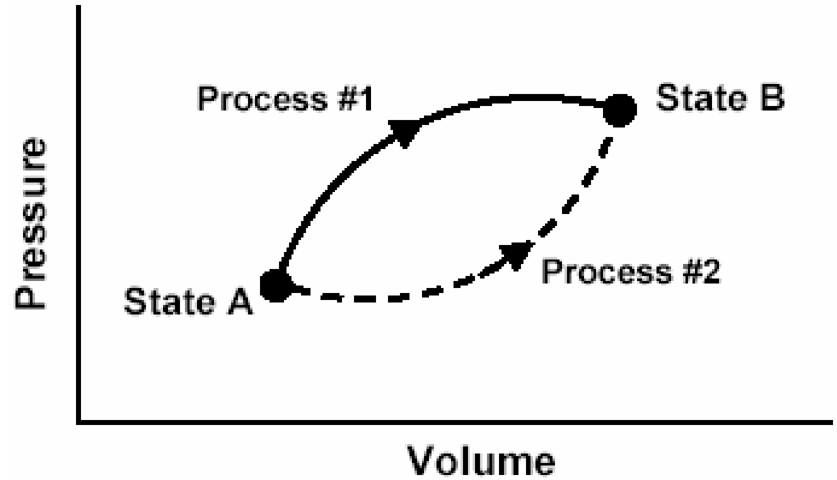
[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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:

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



$$W_1 > W_2$$

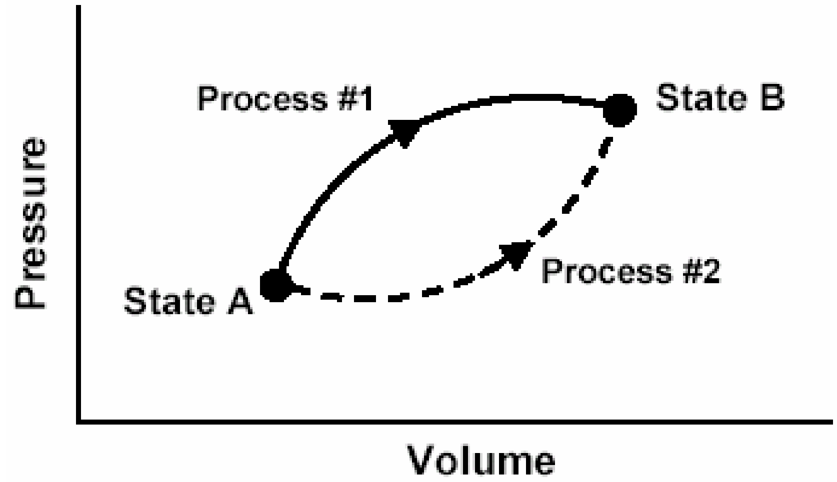
[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

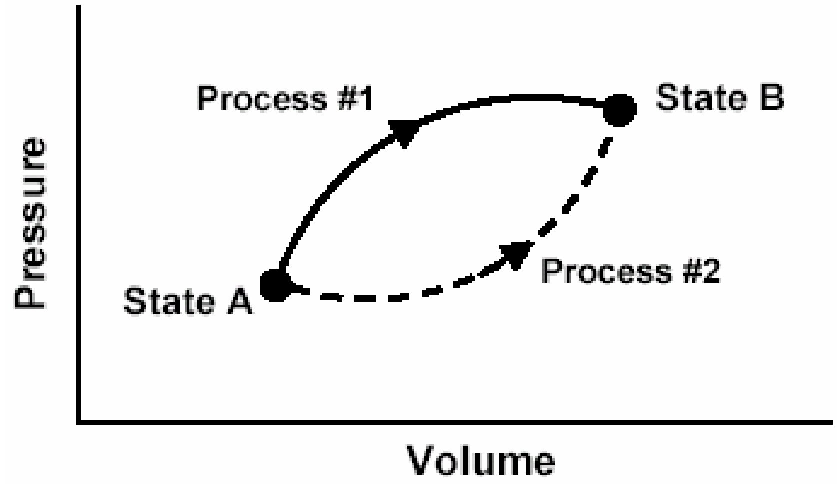
Explanations Given by Thermal Physics Students to Justify $W_1 = W_2$

- "*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:

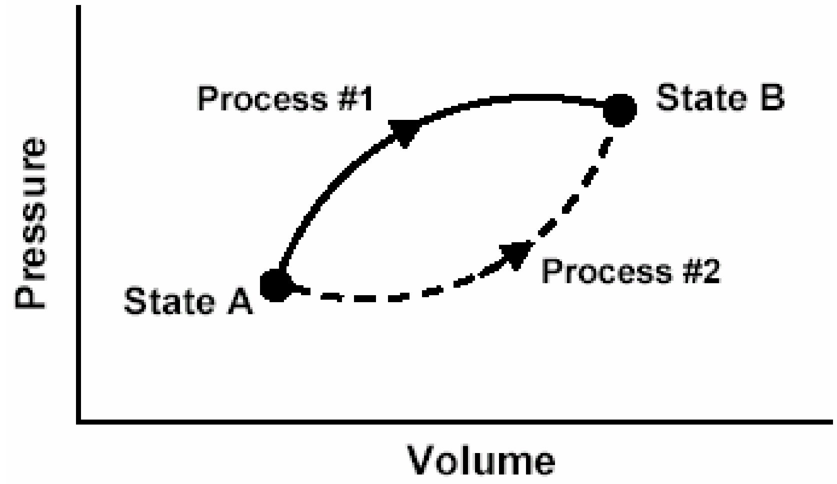


[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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:



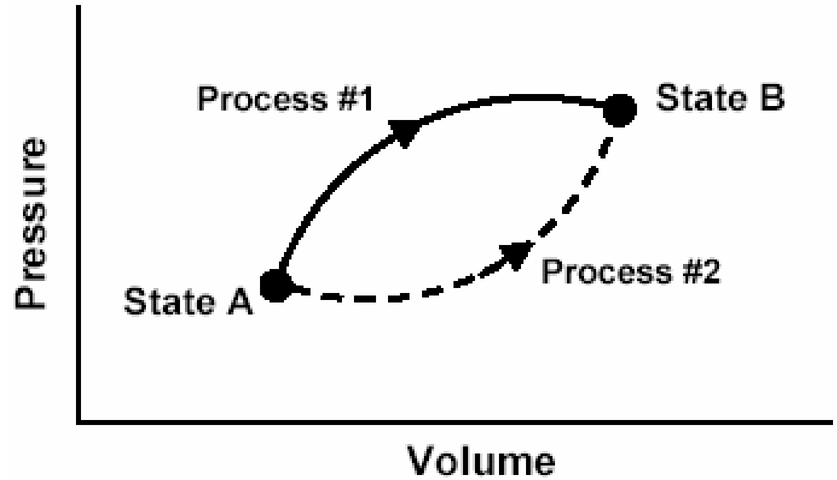
[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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.



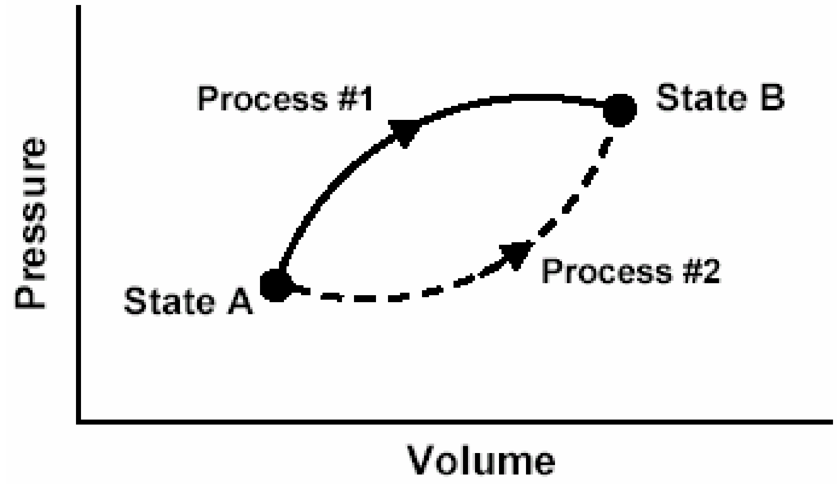
[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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)

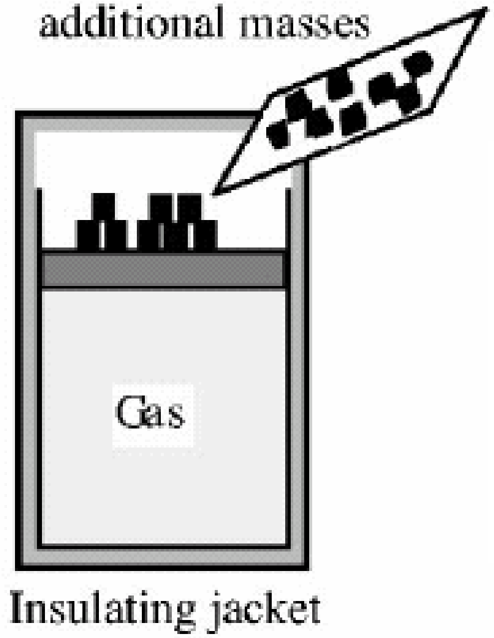
	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**	**2002** **Introductory Physics** **(Post-test)** **Interview Sample** **(*N*=32)**	**2004** **Thermal Physics** **(Pretest)** **(*N*=19)**
$Q_1 > Q_2$	**45%**	**34%**	**30%**
Correct or partially correct explanation	**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

[*From Loverude, Kautz, and Heron (2002)]*

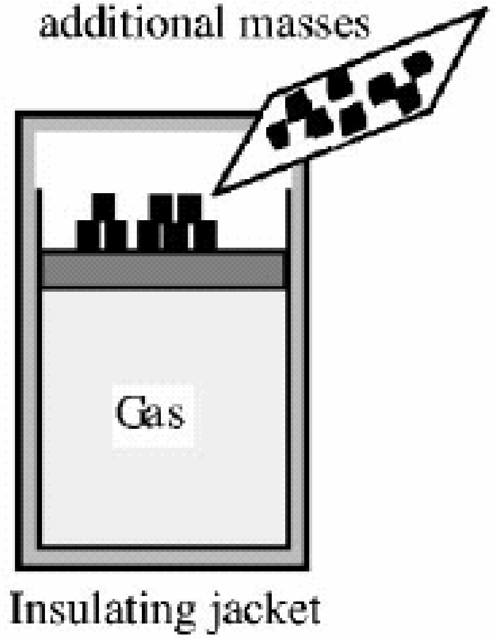


An ideal gas is contained in a cylinder with a tightly fitting piston. Several small masses are on the piston. (See diagram above.)

(Neglect friction between the piston and the cylinder walls.)

The cylinder is placed in an insulating jacket. A large number of masses are added to the piston.

Tell whether the pressure, temperature, and volume of the gas will increase, decrease, or remain the same. Explain.



Correct response regarding temperature (2003 student):

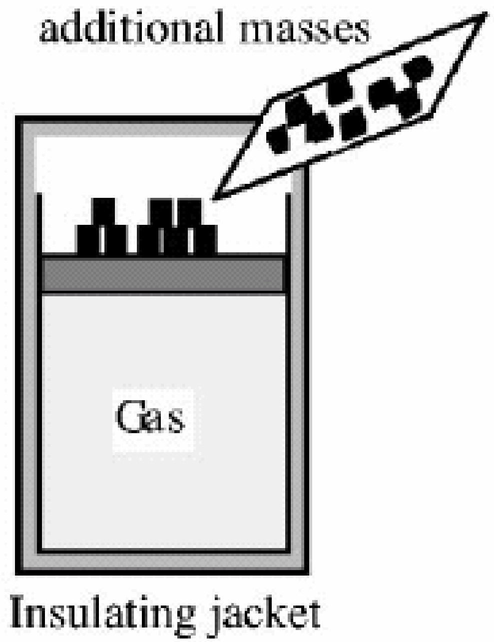
"*Work is done on the gas, but no heat transferred out, so <u>T increases</u>*."

Thermal Physics (Pre-instruction)

Correct responses regarding temperature:

2003: 20% (*N* = 14)

2004: 20% (*N* = 19)



Incorrect responses regarding temperature:

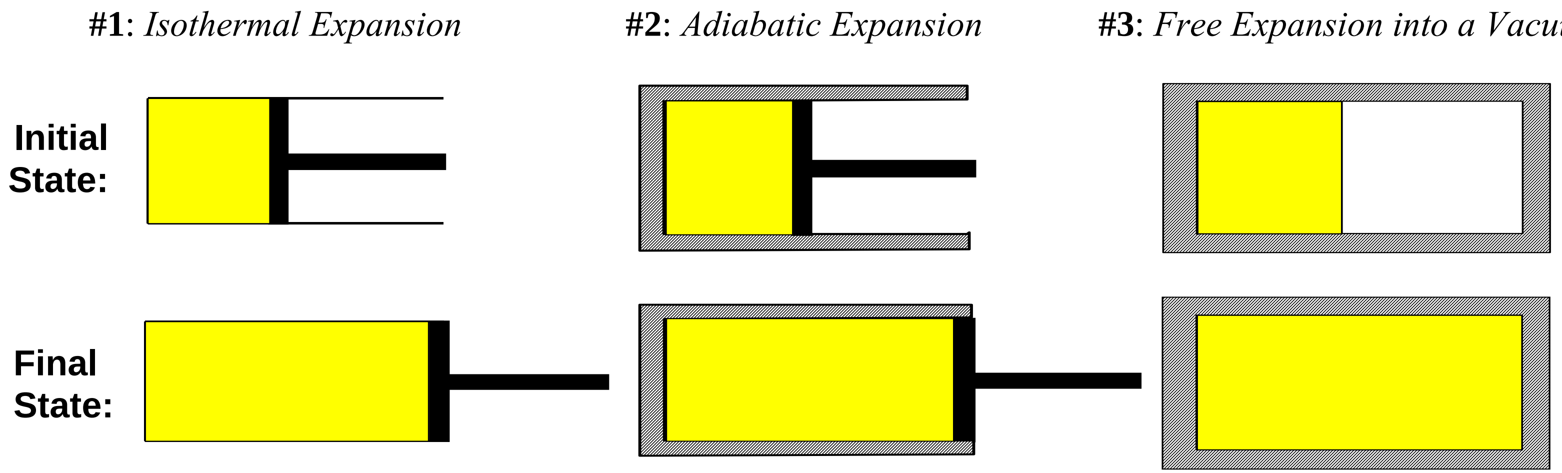
"*The temperature will remain the same because there is no heat transfer*." [2003]

"*Temperature should stay the same due to insulating jacket* ." [2004]

"PV=nRT; T *will stay the same as a drop in* V *will trigger an equal rise in pressure.*" [2004]

[University of Maine question]

A system consisting of one mole of a monatomic *ideal gas* goes through three different processes as shown below. The initial values of volume (V_o), pressure (P_o), and temperature (T_o) are the same for each process. Also note that the final volume (V_f) is the same for each process, and that Processes #1 and #2 occur very slowly.



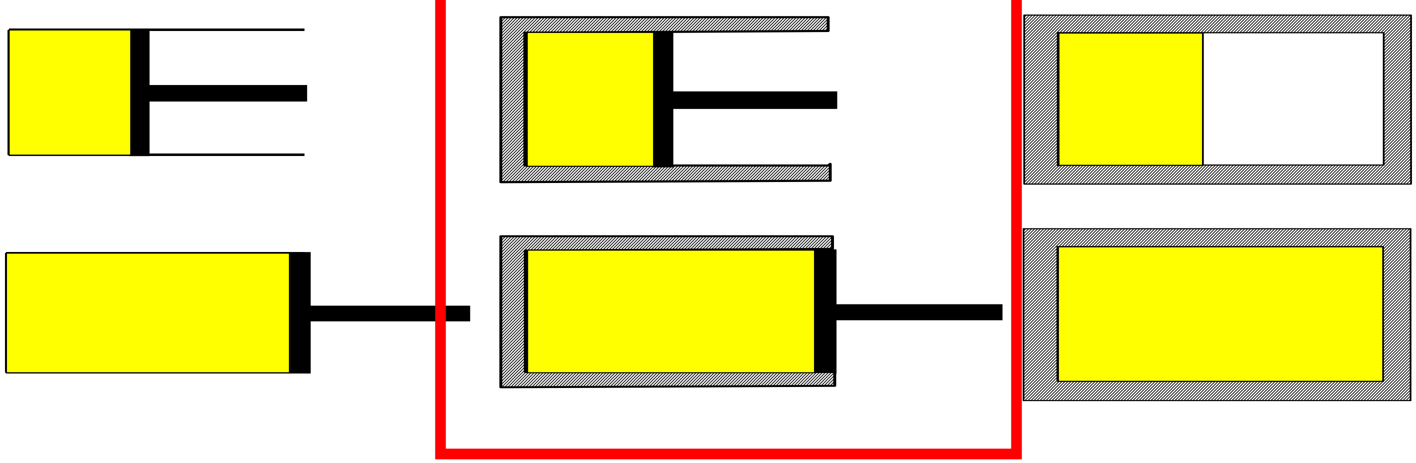
[University of Maine question]

A system consisting of one mole of a monatomic *ideal gas* goes through three different processes as shown below. The initial values of volume (V_o), pressure (P_o), and temperature (T_o) are the same for each process. Also note that the final volume (V_f) is the same for each process, and that Processes #1 and #2 occur very slowly.

#1: *Isothermal Expansion* **#2**: *Adiabatic Expansion* **#3**: *Free Expansion into a Vacuum*

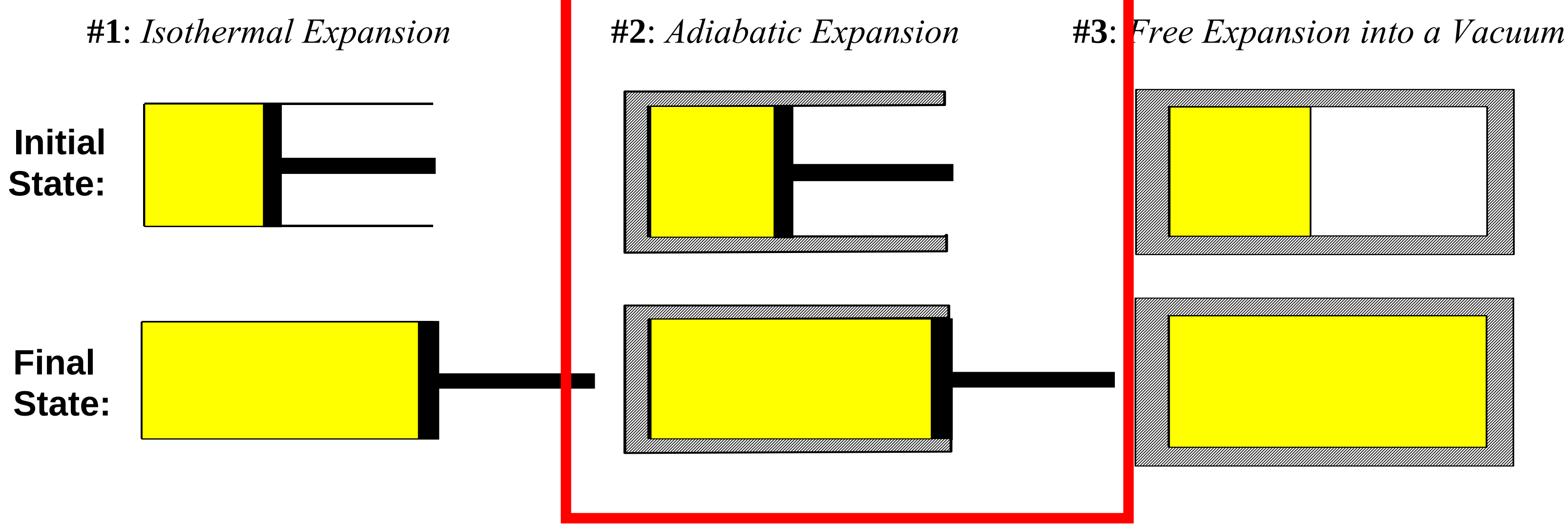
Initial State:

Final State:



[University of Maine question]

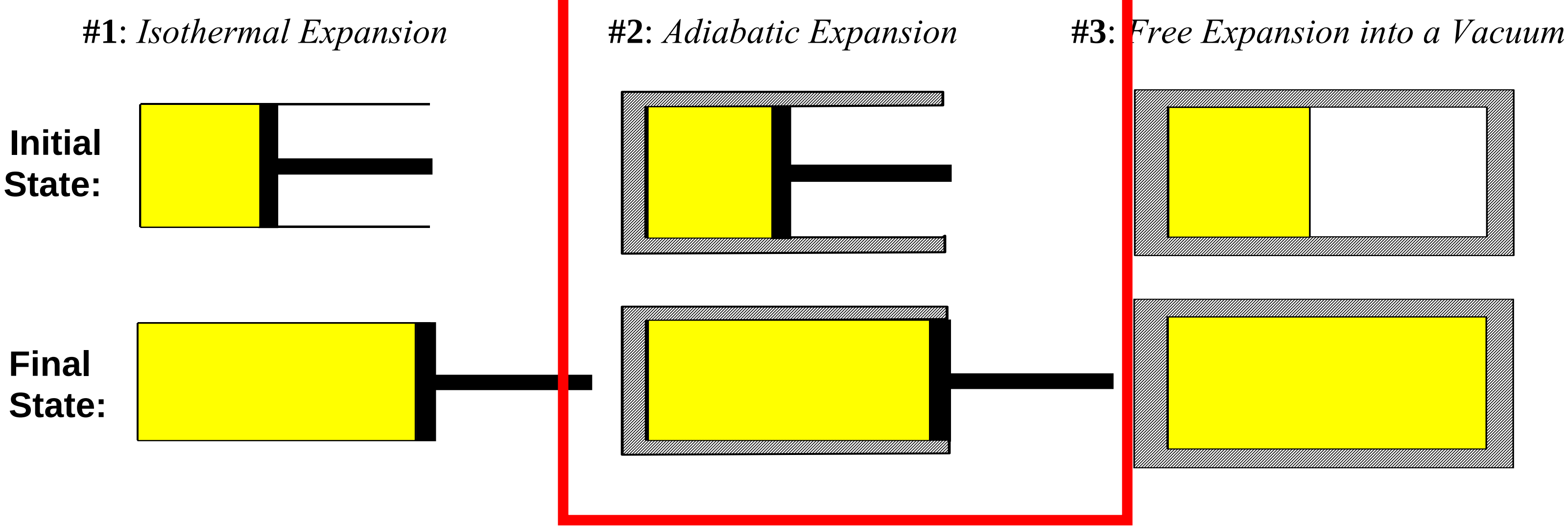
A system consisting of one mole of a monatomic *ideal gas* goes through three different processes as shown below. The initial values of volume (V_o), pressure (P_o), and temperature (T_o) are the same for each process. Also note that the final volume (V_f) is the same for each process, and that Processes #1 and #2 occur very slowly.



Is the change in internal energy *positive*, *negative*, or *zero*?

[University of Maine question]

A system consisting of one mole of a monatomic *ideal gas* goes through three different processes as shown below. The initial values of volume (V_o), pressure (P_o), and temperature (T_o) are the same for each process. Also note that the final volume (V_f) is the same for each process, and that Processes #1 and #2 occur very slowly.



Is the change in internal energy *positive*, *negative*, or *zero*?

No heat transfer to the system, but the system loses energy by doing work on surroundings $\Rightarrow$ change in internal energy is *negative*

2004 Thermal Physics, N = 17*

	Adiabatic-expansion problem correct on final exam	Adiabatic-expansion problem incorrect on final exam
Insulated-piston problem correct on pretest		
Insulated-piston problem incorrect on pretest		

2004 Thermal Physics, $N = 17$*

	Adiabatic-expansion problem correct on final exam	Adiabatic-expansion problem incorrect on final exam
Insulated-piston problem correct on pretest		
Insulated-piston problem incorrect on pretest		

*two students failed to show up for final

2004 Thermal Physics, $N = 17$

	Adiabatic-expansion problem correct on final exam	Adiabatic-expansion problem incorrect on final exam
Insulated-piston problem correct on pretest	24%	0%
Insulated-piston problem incorrect on pretest		

2004 Thermal Physics, N = 17

	Adiabatic-expansion problem correct on final exam	Adiabatic-expansion problem incorrect on final exam
Insulated-piston problem correct on pretest	24%	0%
Insulated-piston problem incorrect on pretest	59%	

2004 Thermal Physics, $N = 17$

	Adiabatic-expansion problem correct on final exam	Adiabatic-expansion problem incorrect on final exam
Insulated-piston problem correct on pretest	24%	0%
Insulated-piston problem incorrect on pretest	59%	18%

2004 Thermal Physics, N = 17

	Adiabatic-expansion problem correct on final exam	Adiabatic-expansion problem incorrect on final exam
Insulated-piston problem correct on pretest	24%	0%
Insulated-piston problem incorrect on pretest	59%	18%

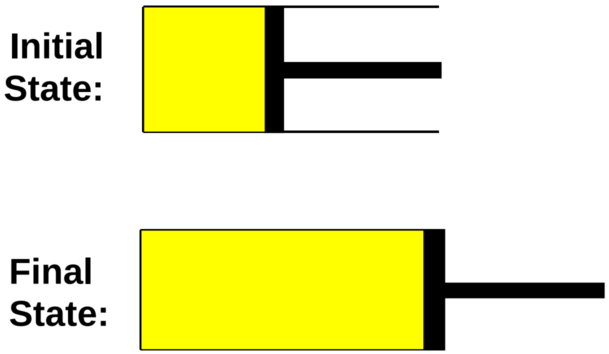
Is the insulated-piston problem more difficult?

A Special Difficulty: Free Expansion

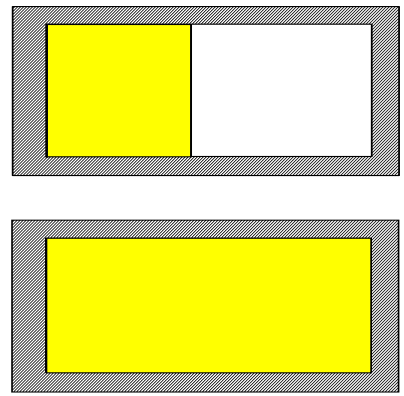
[University of Maine question]

A system consisting of one mole of a monatomic *ideal gas* goes through three different processes as shown below. The initial values of volume (V_o), pressure (P_o), and temperature (T_o) are the same for each process. Also note that the final volume (V_f) is the same for each process, and that Processes #1 and #2 occur very slowly.

#1: *Isothermal Expansion*



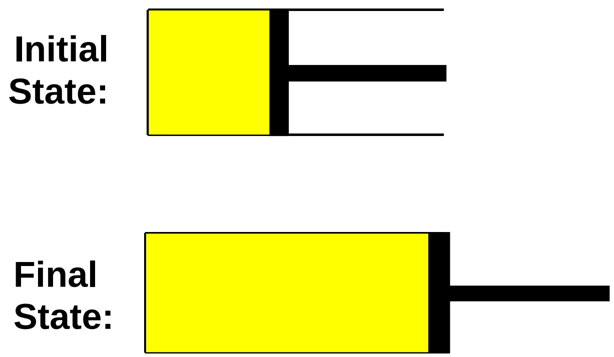
#3: *Free Expansion into a Vacuum*



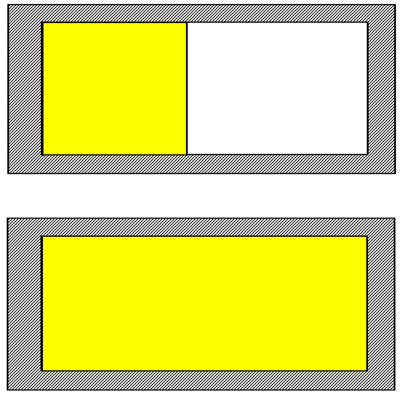
[University of Maine question]

A system consisting of one mole of a monatomic *ideal gas* goes through three different processes as shown below. The initial values of volume (V_o), pressure (P_o), and temperature (T_o) are the same for each process. Also note that the final volume (V_f) is the same for each process, and that Processes #1 and #2 occur very slowly.

#1: *Isothermal Expansion*



#3: *Free Expansion into a Vacuum*



Students were asked to rank magnitudes of *Q*, *W*, Δ*U*, and Δ*S* for #1 and #3

(initial and final states are the same for both)

A Special Difficulty: Free Expansion

- Discussed extensively in class in context of entropy's state-function property
  - group work using worksheets
  - homework assignment
- Poor performance on 2004 final-exam question in advanced course (< 50% correct)
  - frequent errors: belief that temperature or internal energy must change, work is done, etc.
  - difficulties with first-law concepts prevented students from realizing that T does not change

Consistent with U. Maine results

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

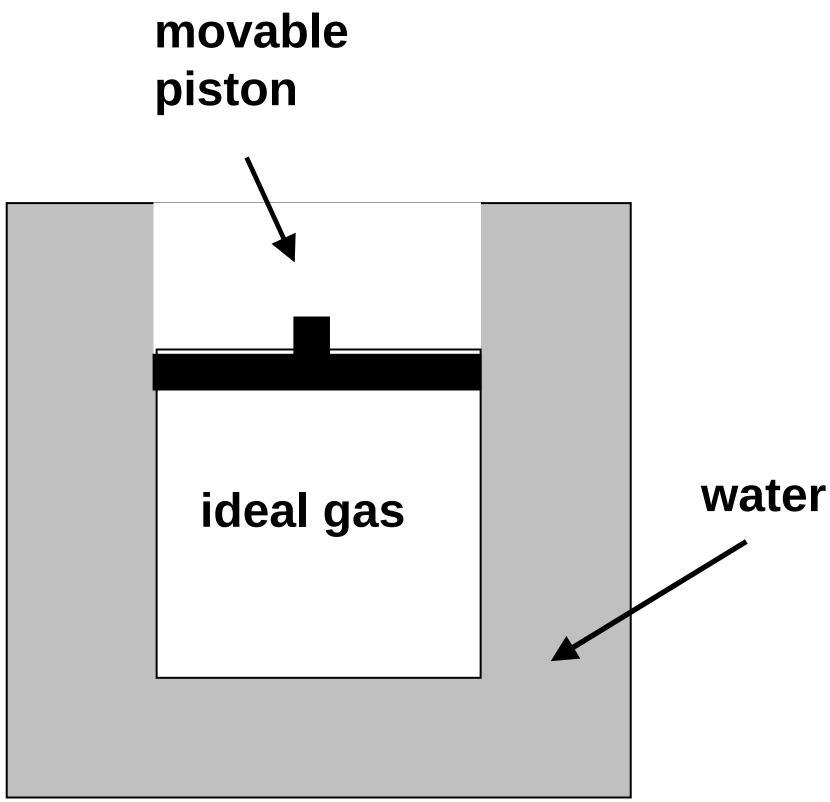
A fixed quantity of ideal gas is contained within a metal cylinder that is sealed with a movable, frictionless, insulating piston.

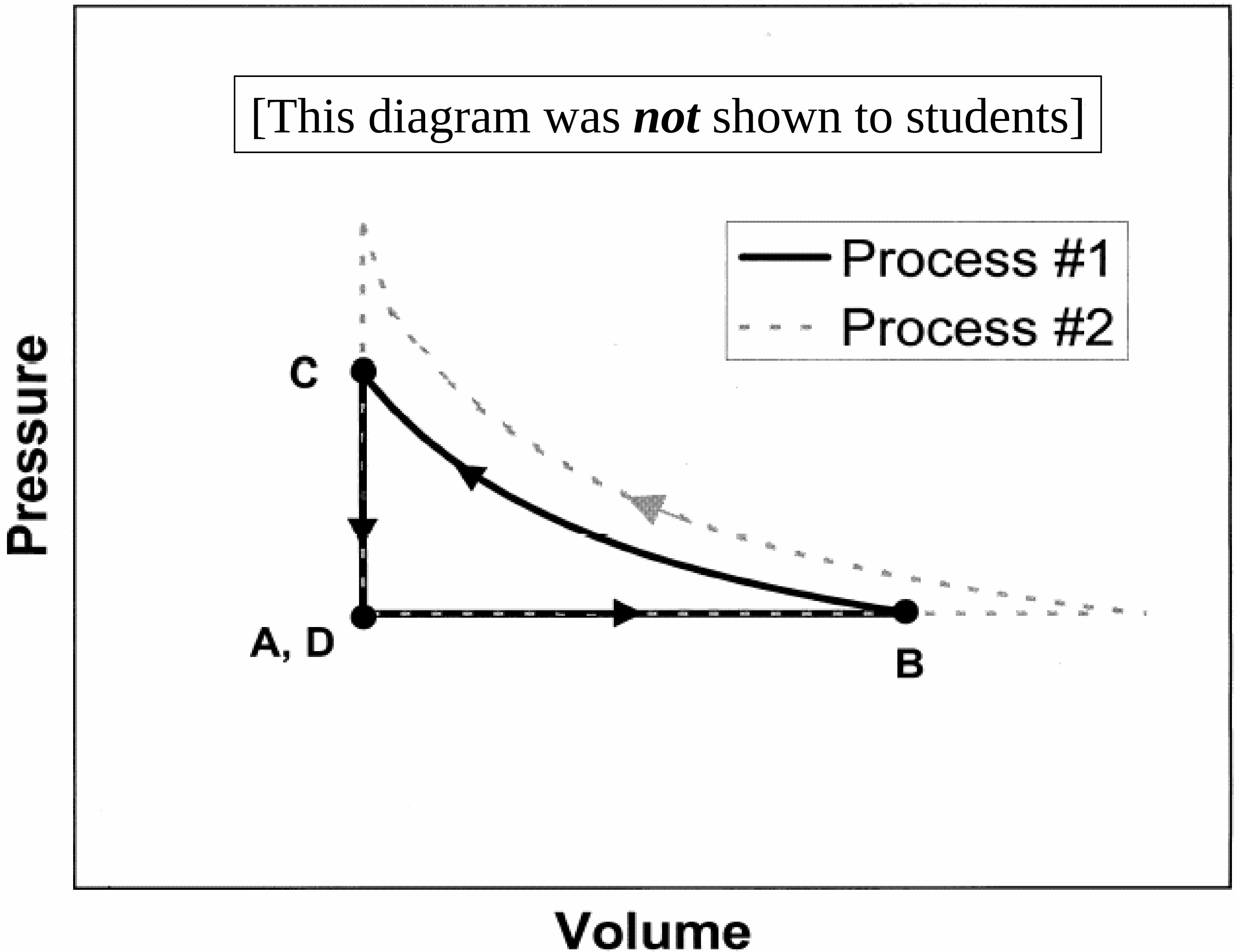
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

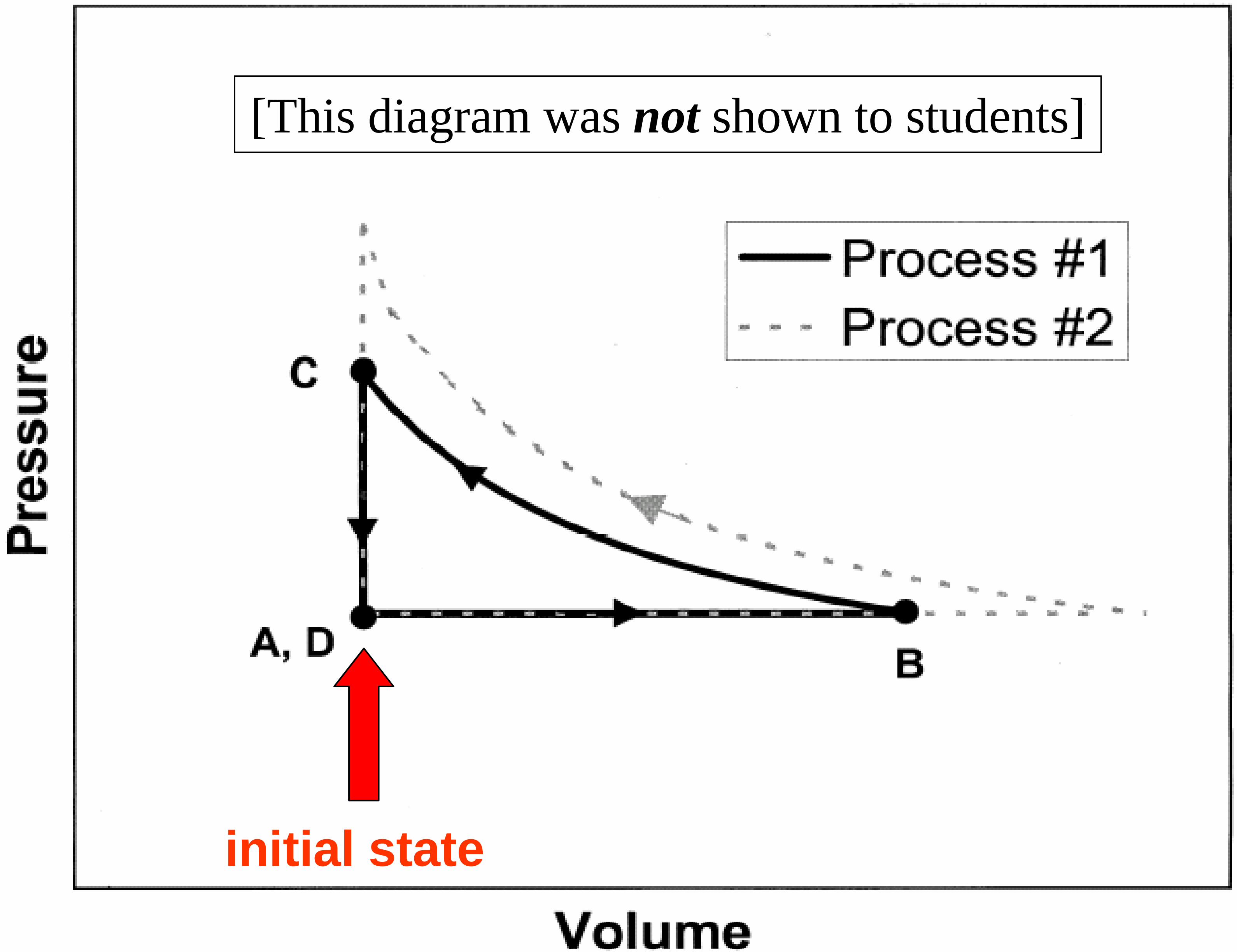
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature

Time *A*

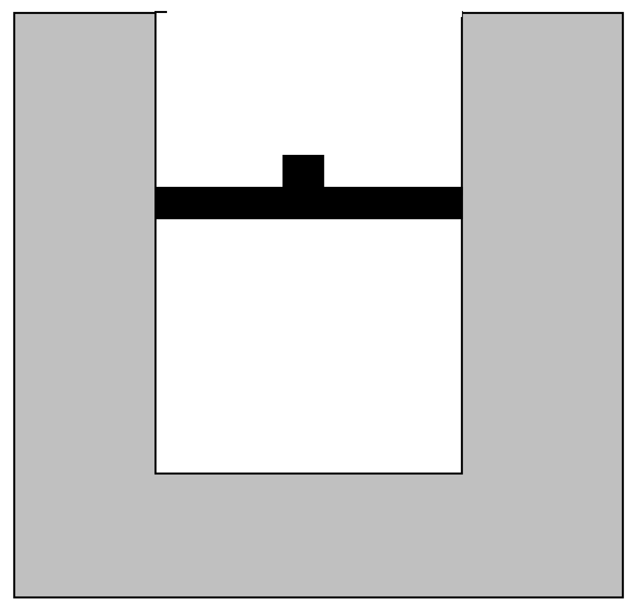
Entire system at room temperature.

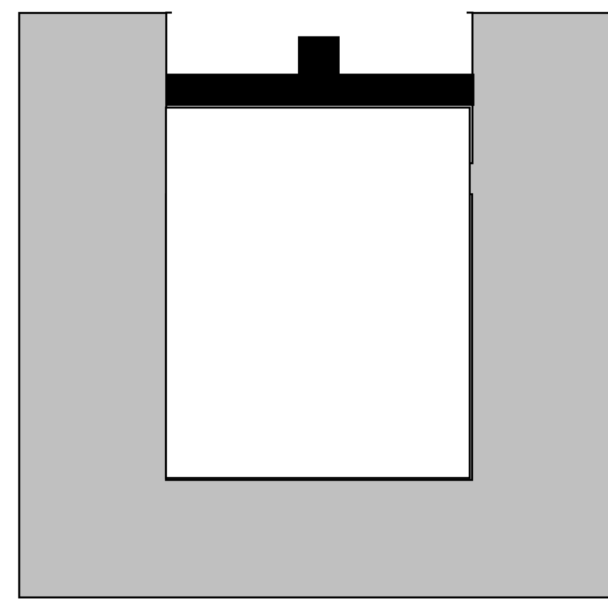



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

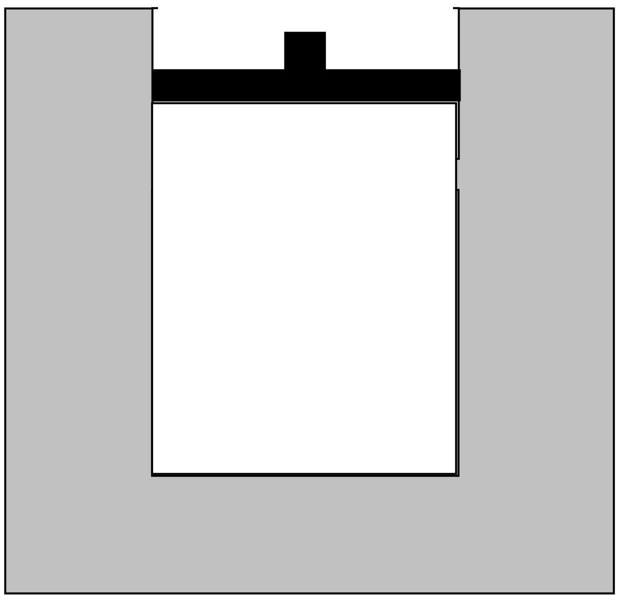

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
initial state
Pressure
Volume

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

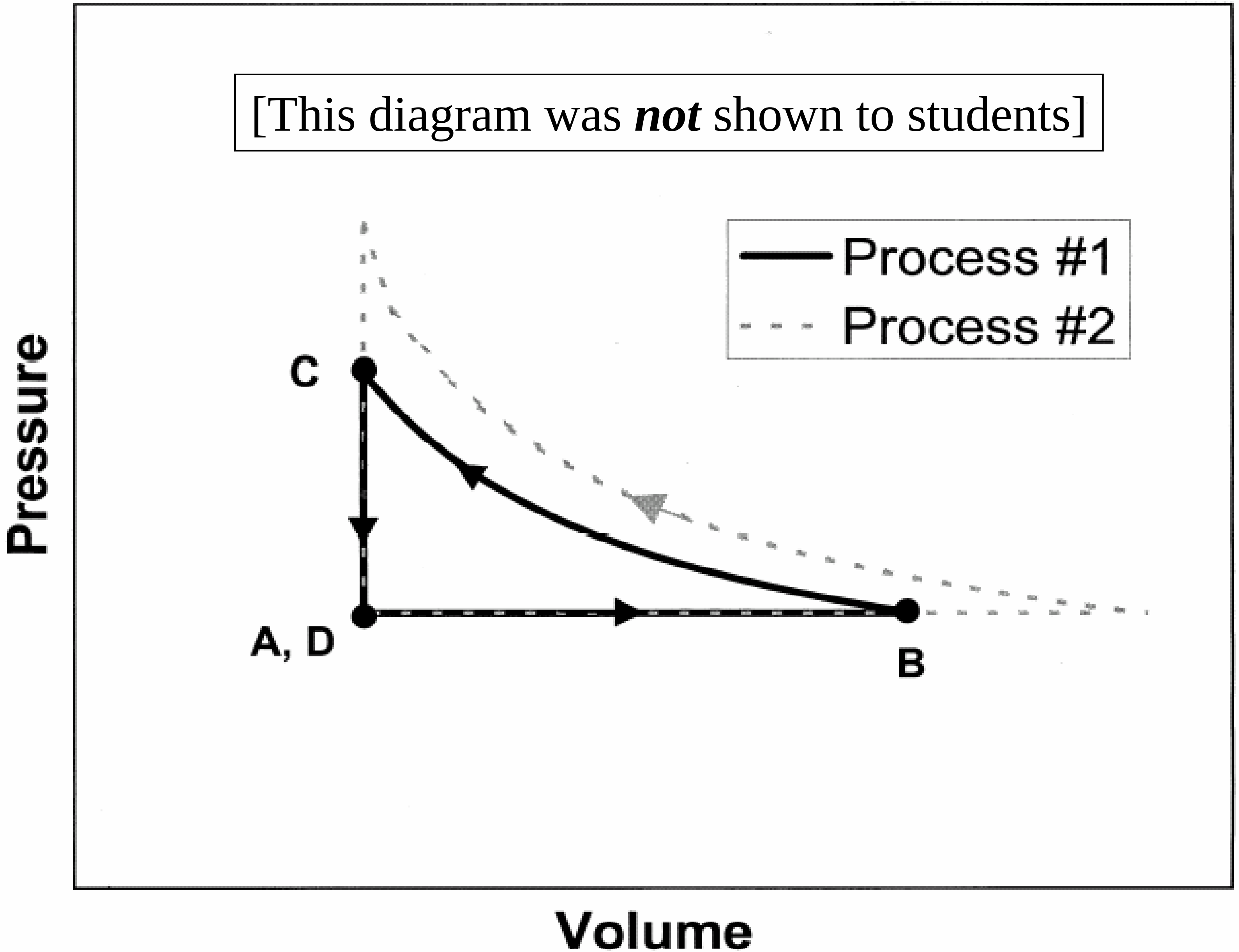


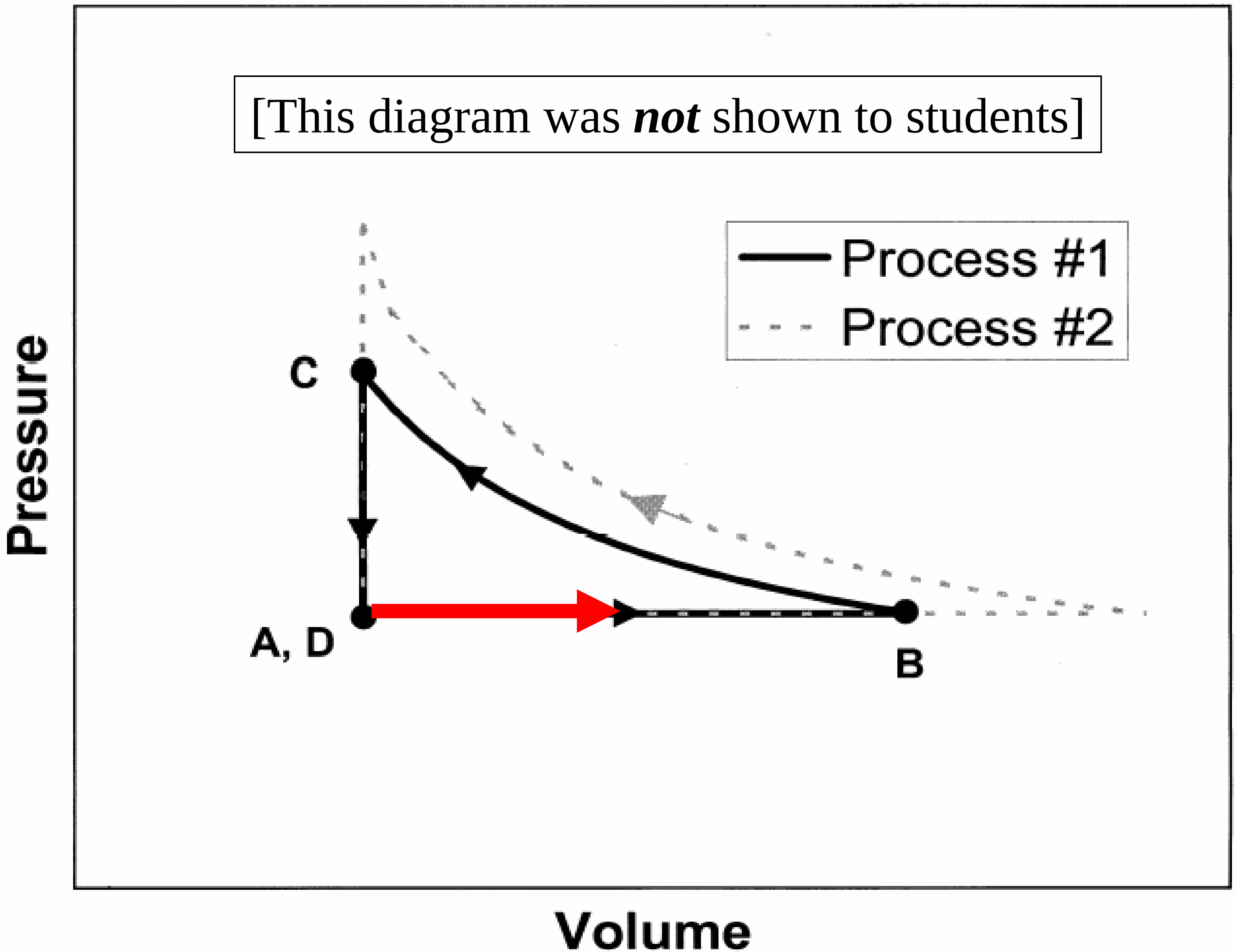


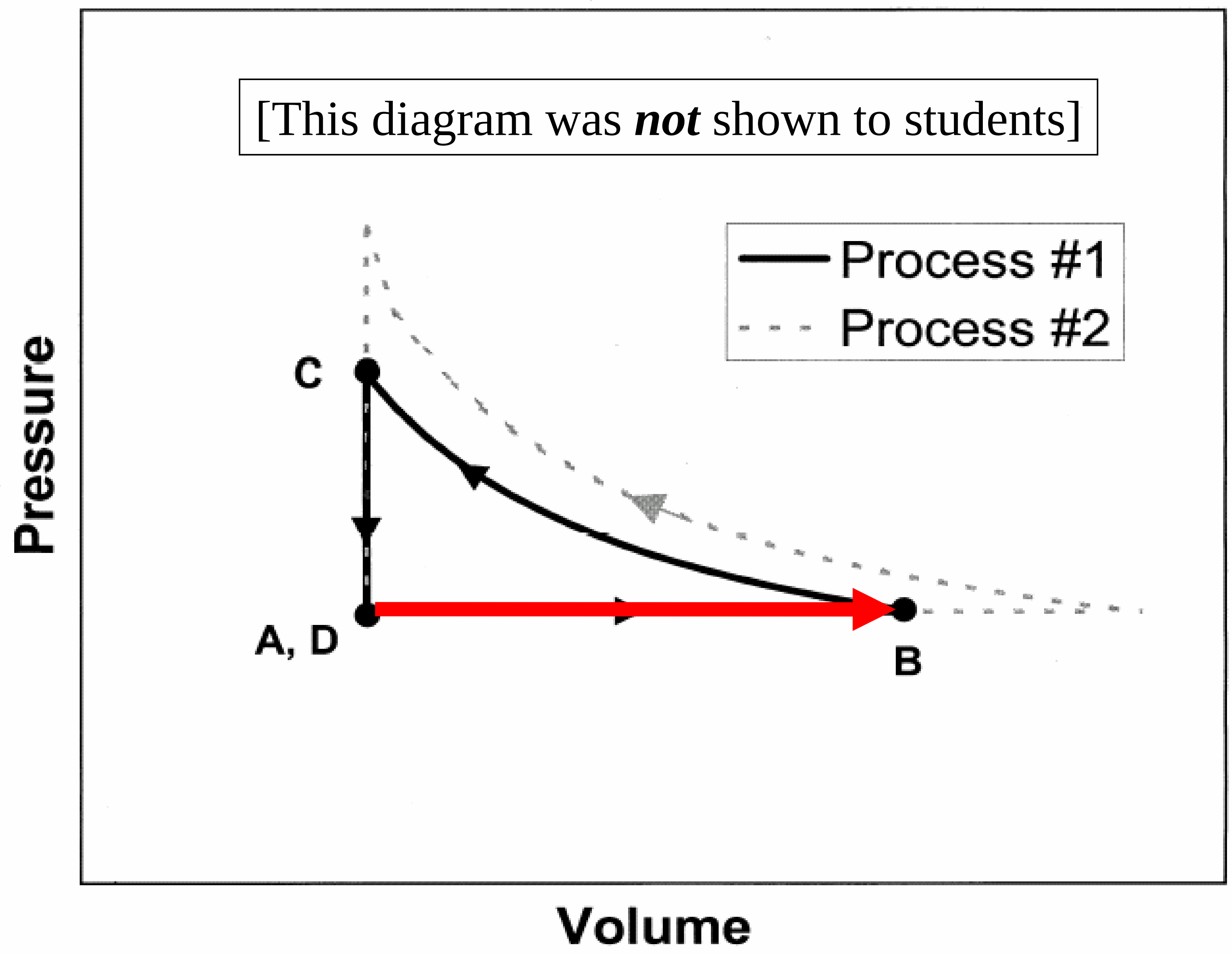
At time ***B*** the heating of the water stops, and the piston stops moving

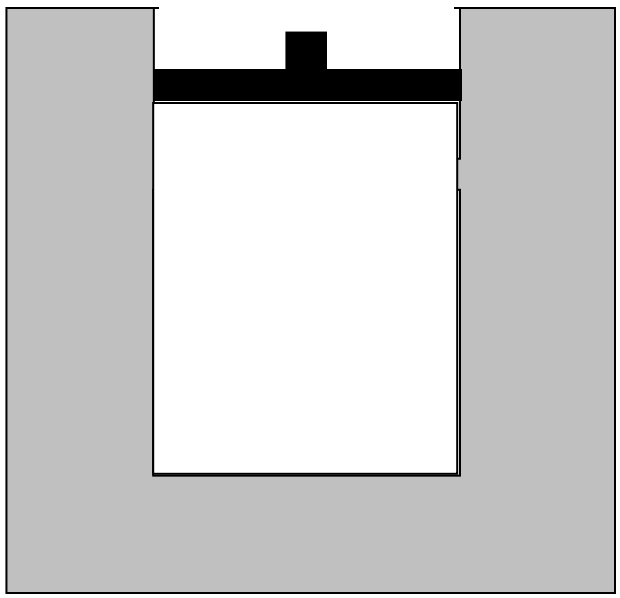


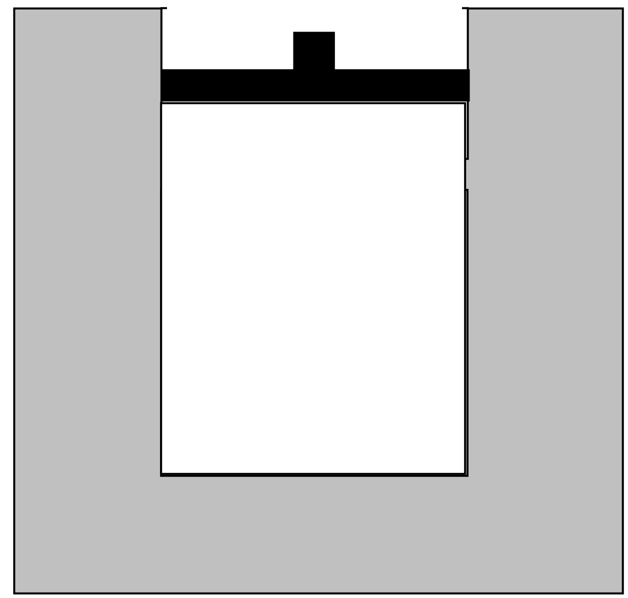
[This diagram was ***not*** shown to students]



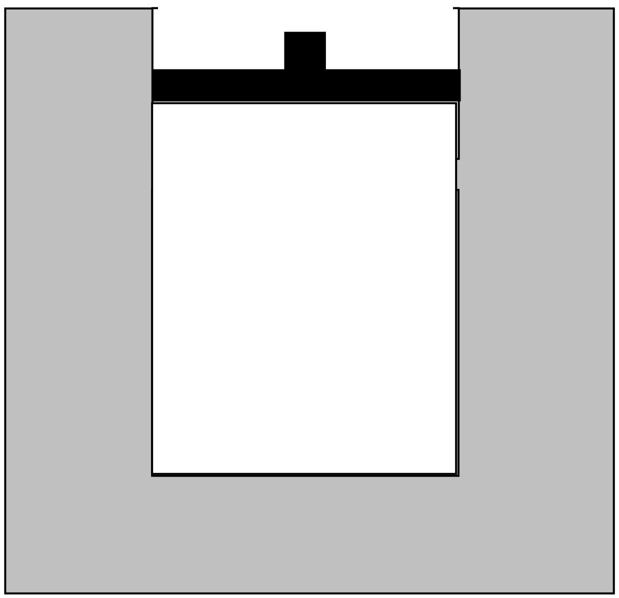

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume


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





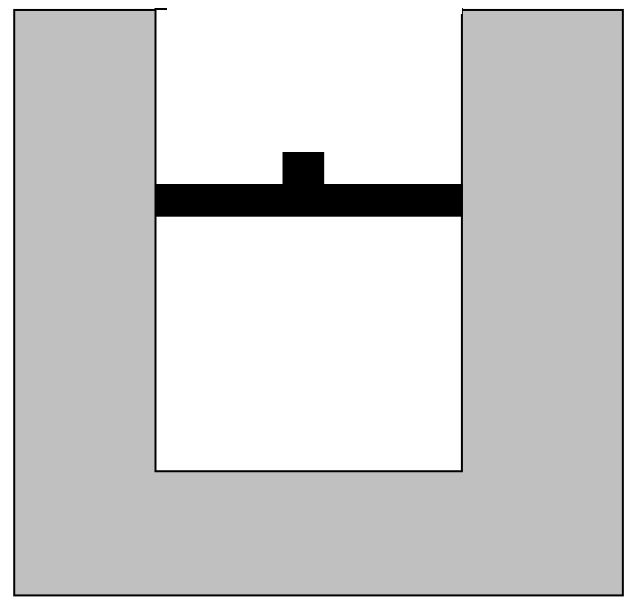
Question #1: During the process that occurs from time *A* to time *B*, which of the following is true: (a) positive work is done *on* the gas *by* the environment, (b) positive work is done *by* the gas *on* the environment, (c) no *net* work is done on or by the gas.

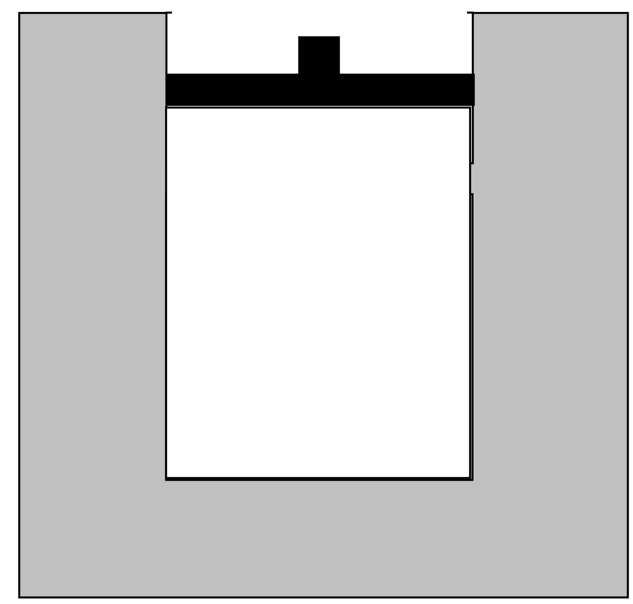


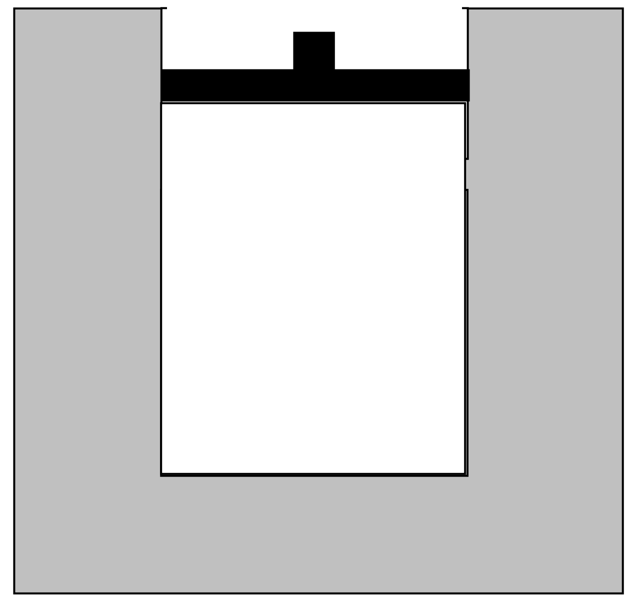
Question #1: During the process that occurs from time *A* to time *B*, which of the following is true: (a) positive work is done *on* the gas *by* the environment, (b) positive work is done *by* the gas *on* the environment, (c) no *net* work is done on or by the gas.

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

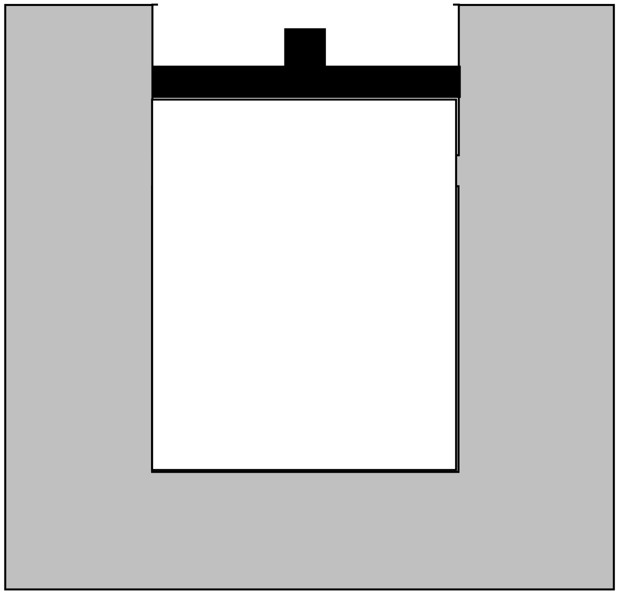
- Basic notion of thermodynamics: if part or all of system boundary is displaced during quasistatic process, energy is transferred between system and surroundings in the form of “work.”
- Study of Loverude, Kautz, and Heron (2002) showed that few students could spontaneously invoke concept of work in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

(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%

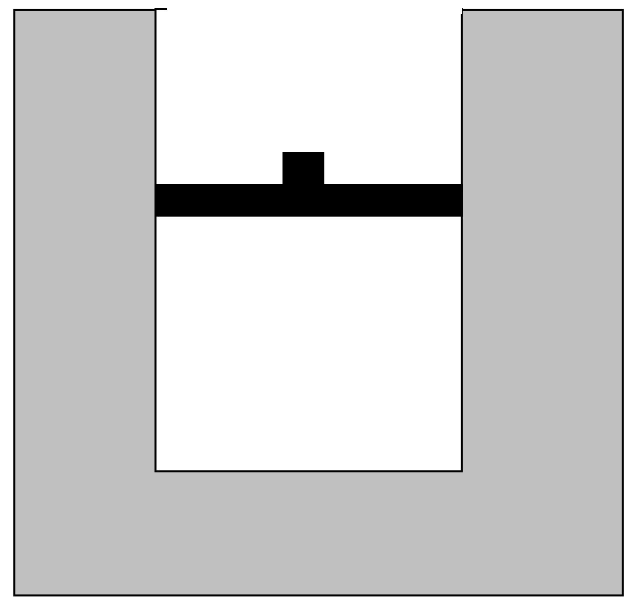
Sample explanations for (a) answer:

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

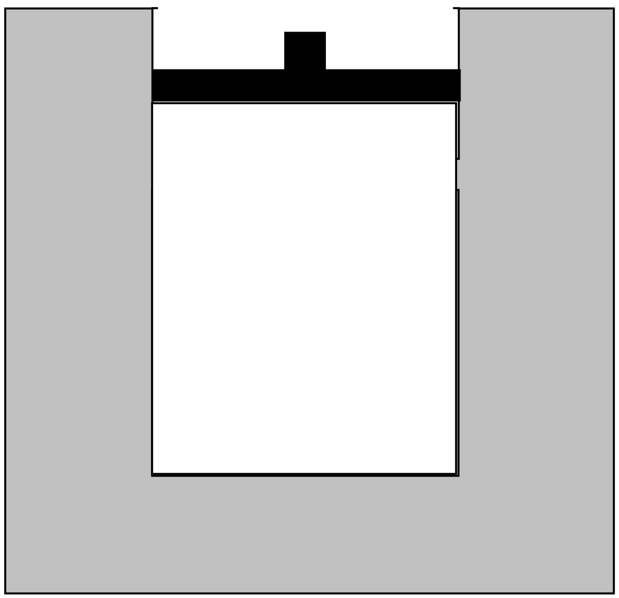
"The environment did work on the gas, since it made the gas expand and the piston moved up . . . water was heating up, doing work on the gas, making it expand."

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

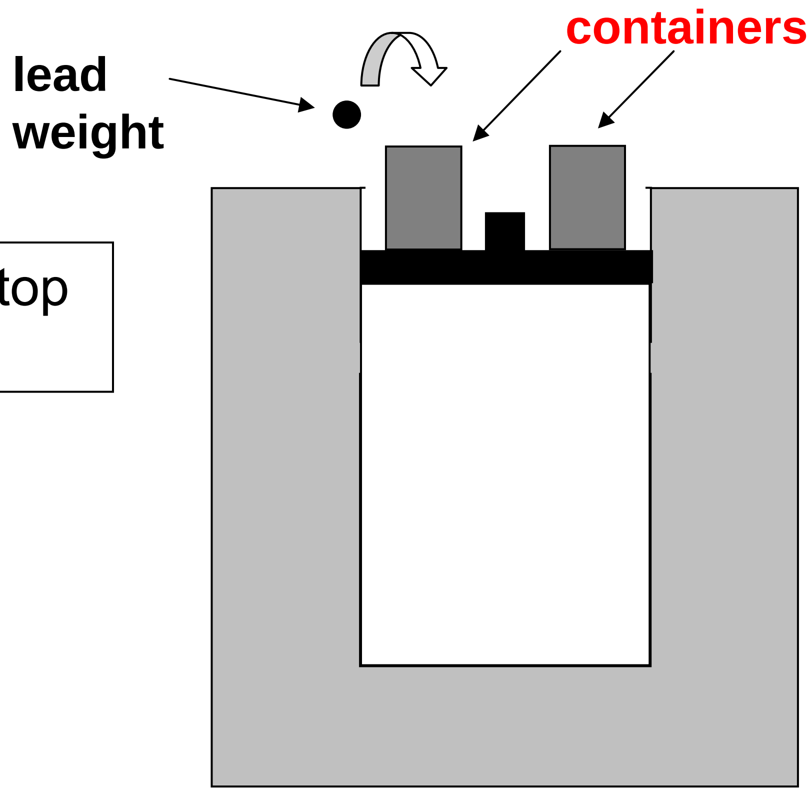
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.



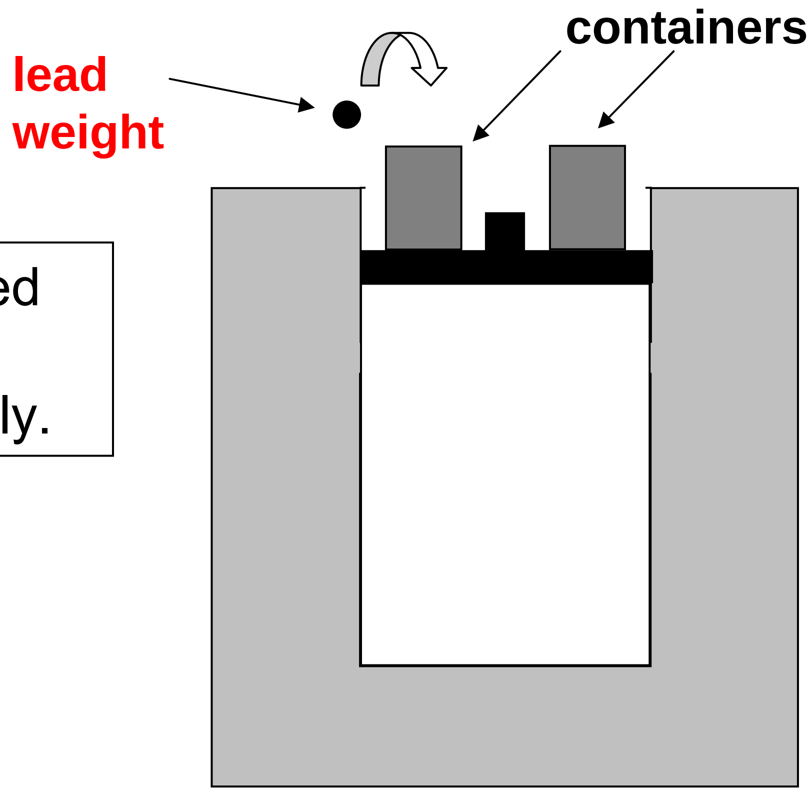
At time ***B*** the heating of the water stops, and the piston stops moving

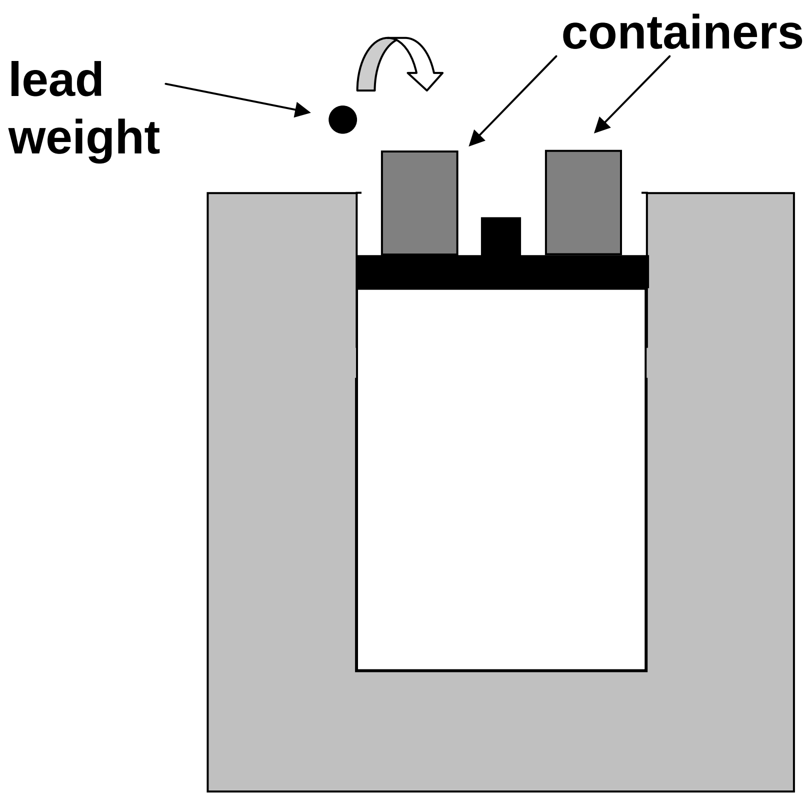


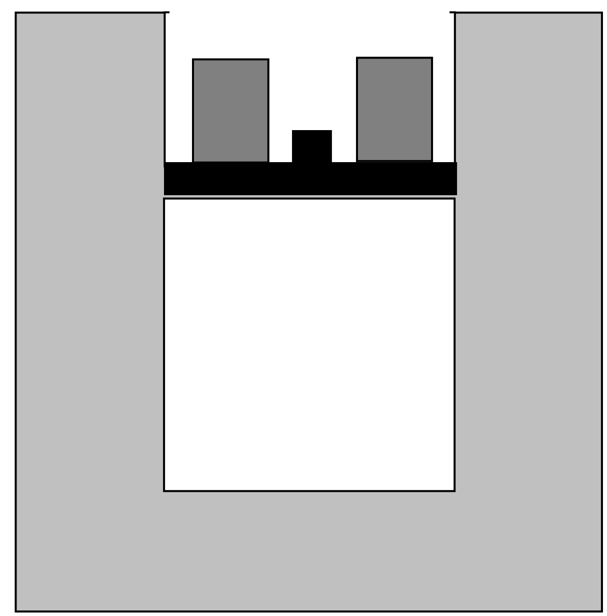
Now, empty containers are placed on top of the piston as shown.



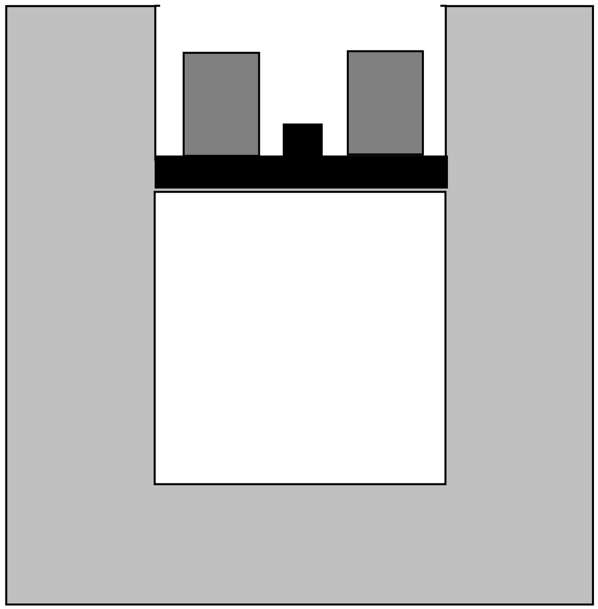
Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly.



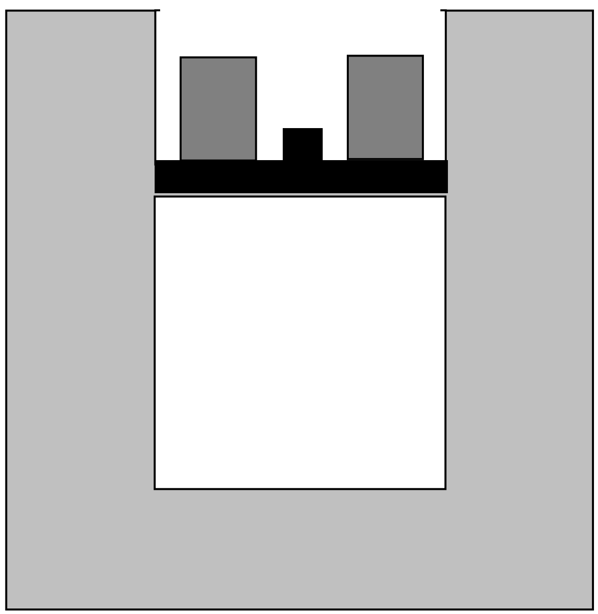

containers
lead
weight

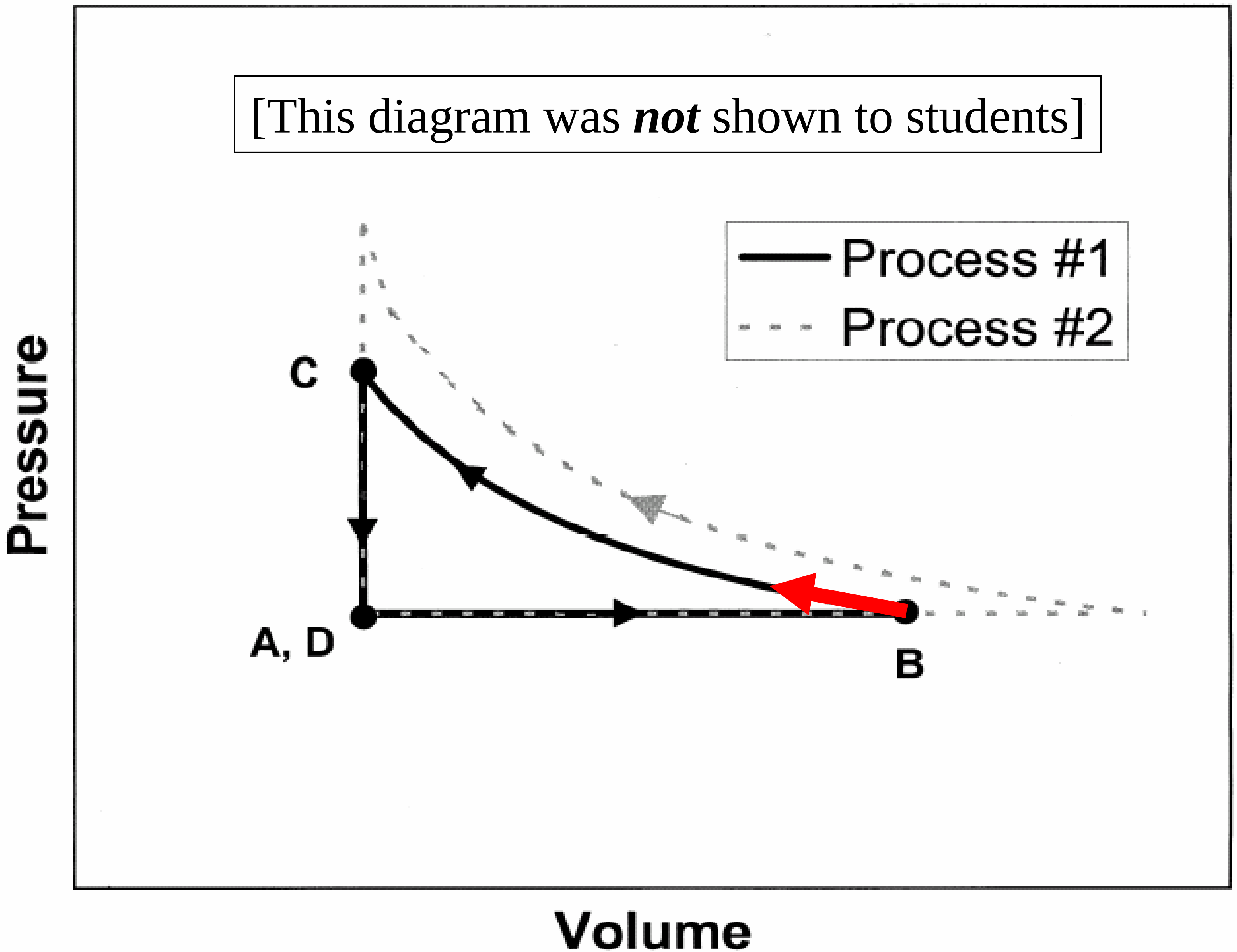


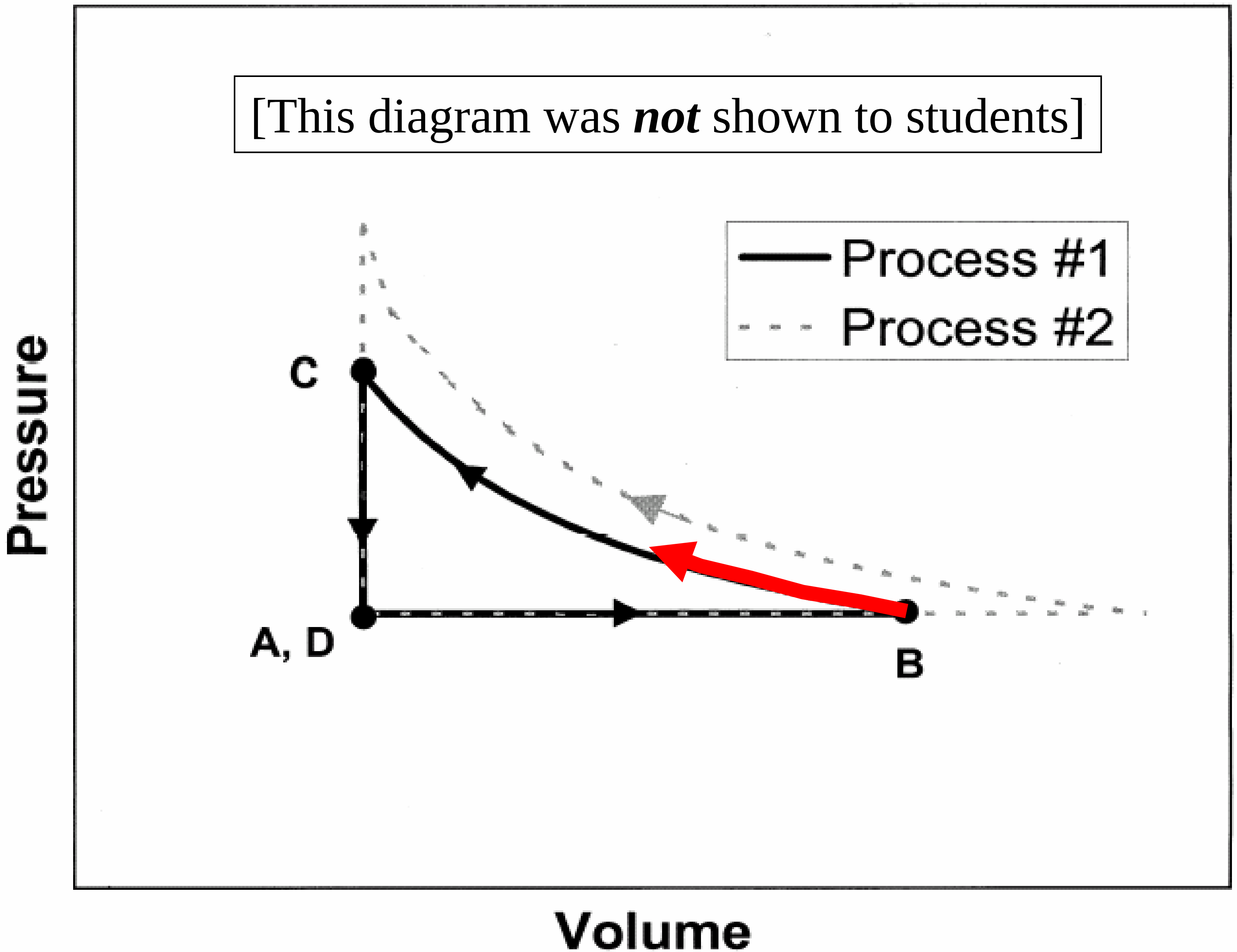
While this happens the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*.

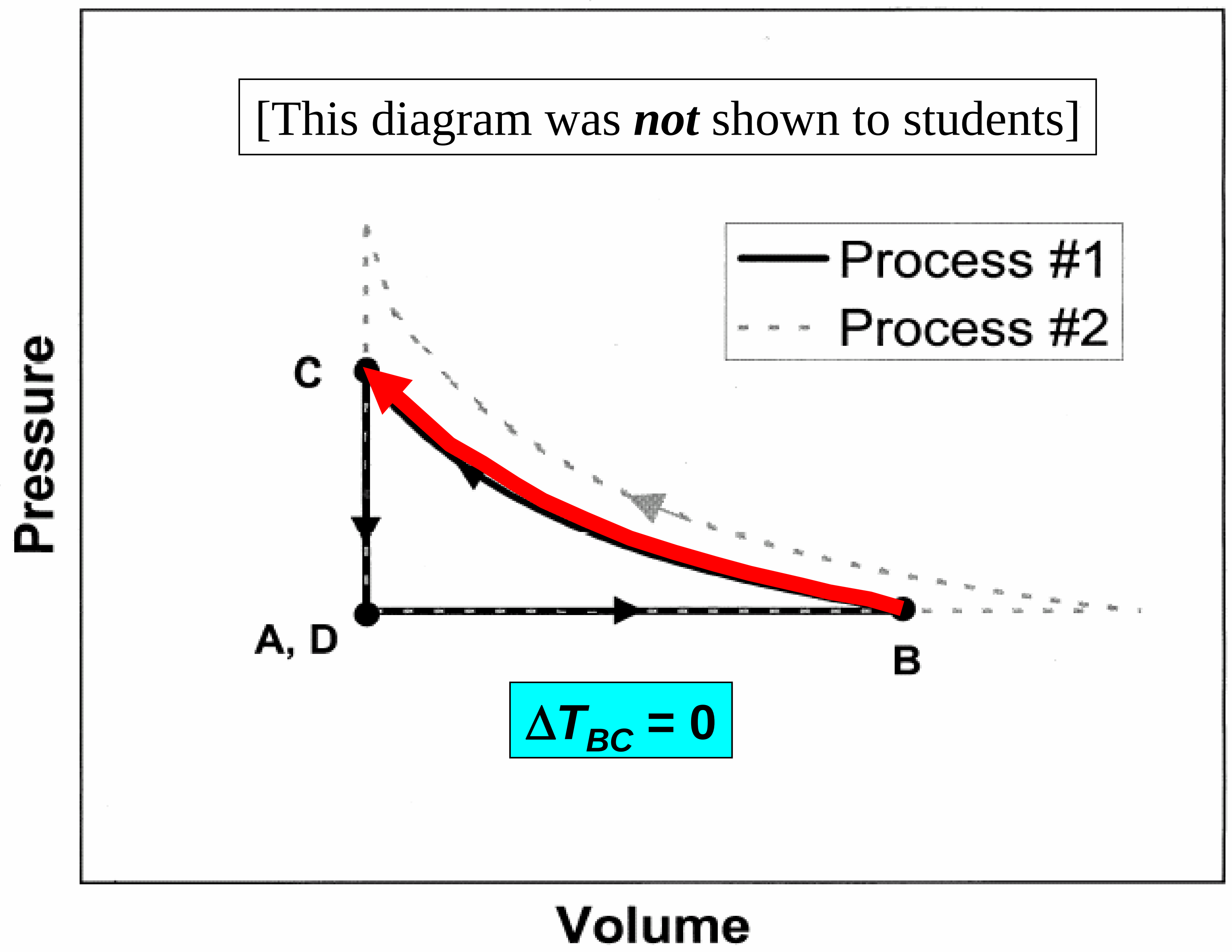


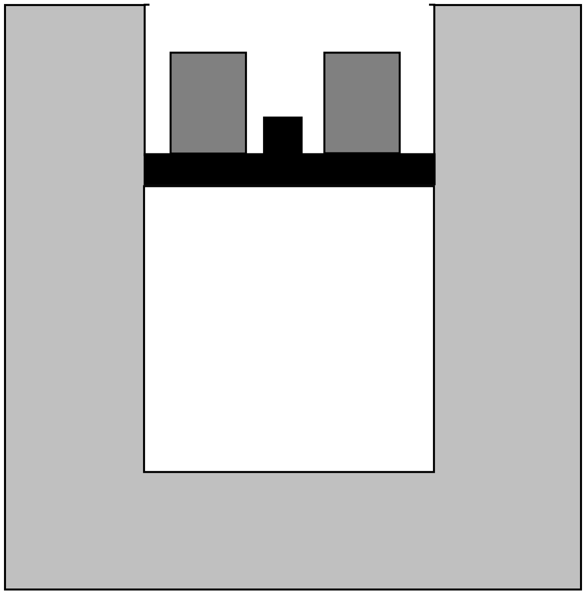
At time ***C*** we stop adding lead weights to the container and the piston stops moving. The piston is now at exactly the same position it was at time ***A*** .



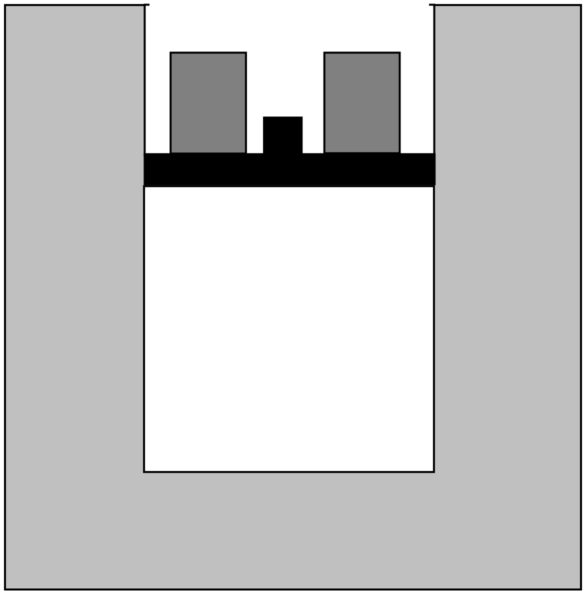

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume


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

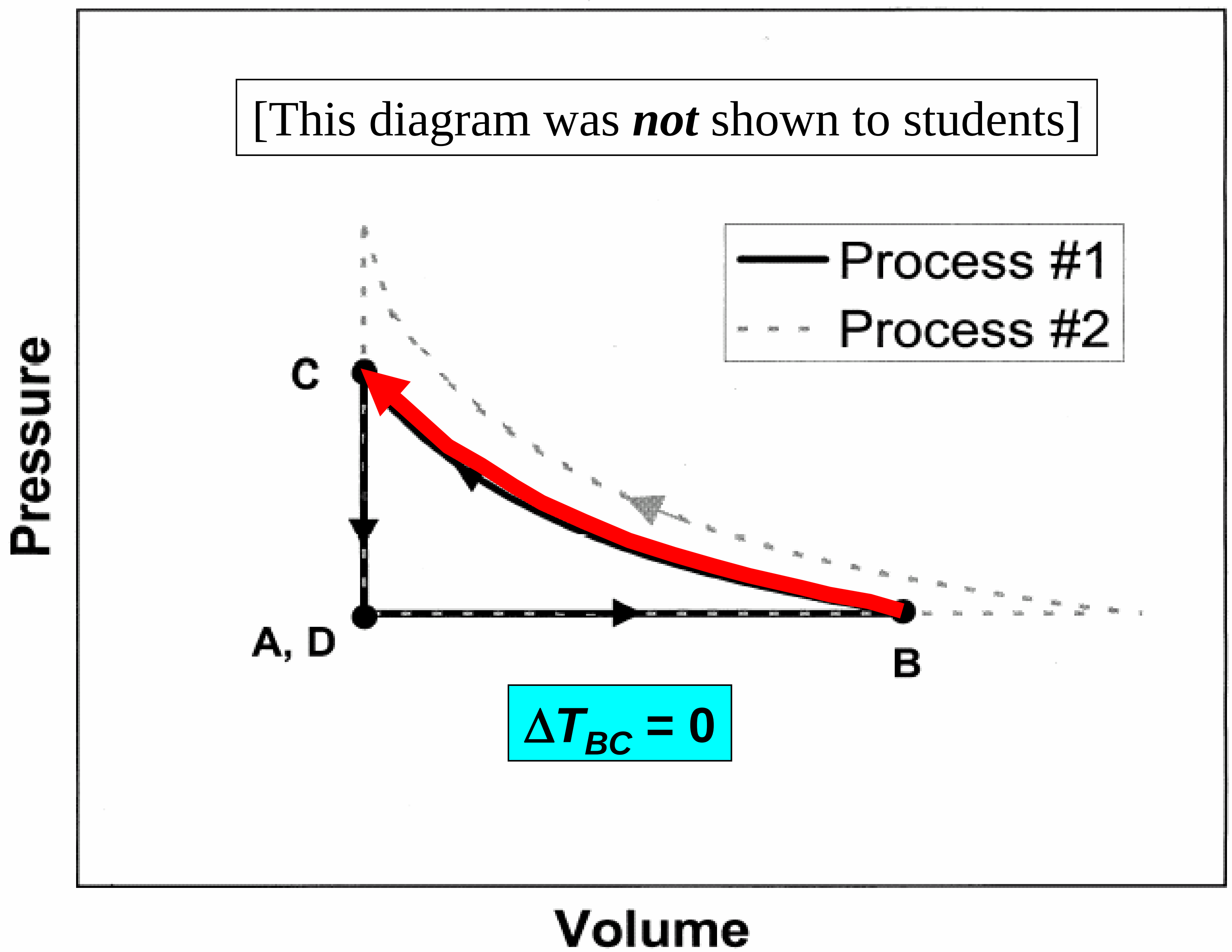

[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
$\Delta T_{BC} = 0$
Pressure
Volume

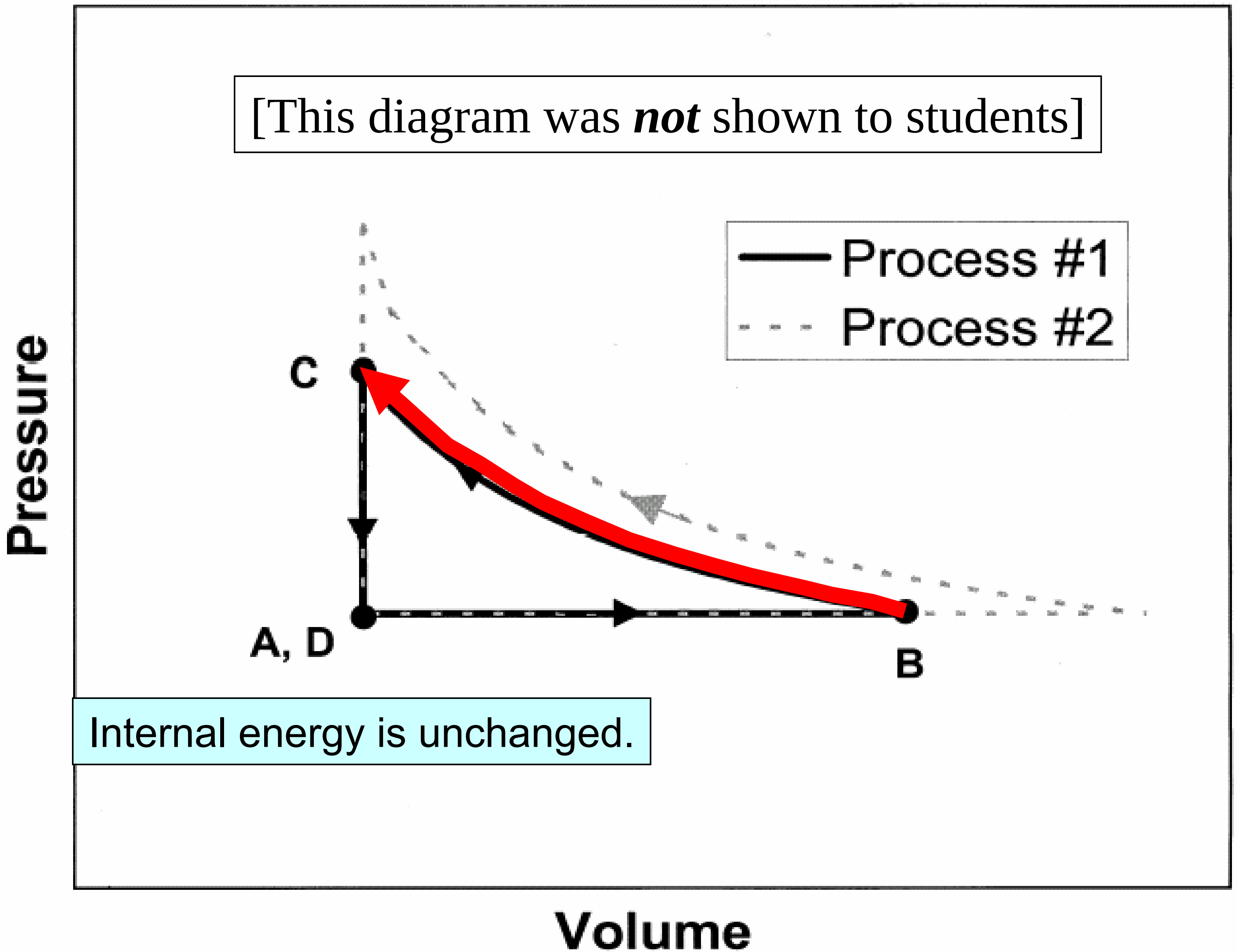


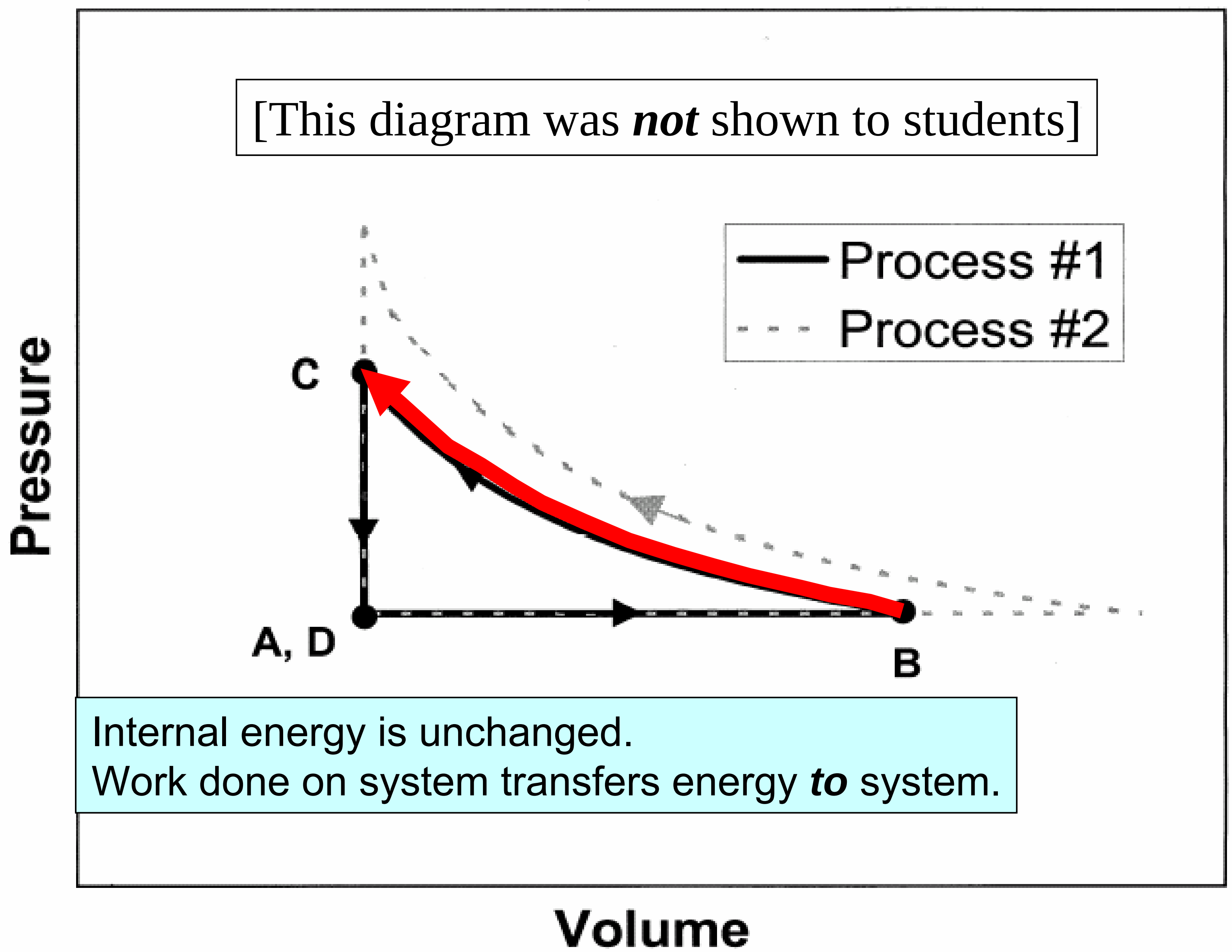
Question #4: During the process that occurs from time *B* to time *C*, is there *any* net energy flow between the gas and the water? If no, explain why not. If yes, is there a net flow of energy from gas to water, or from water to gas?

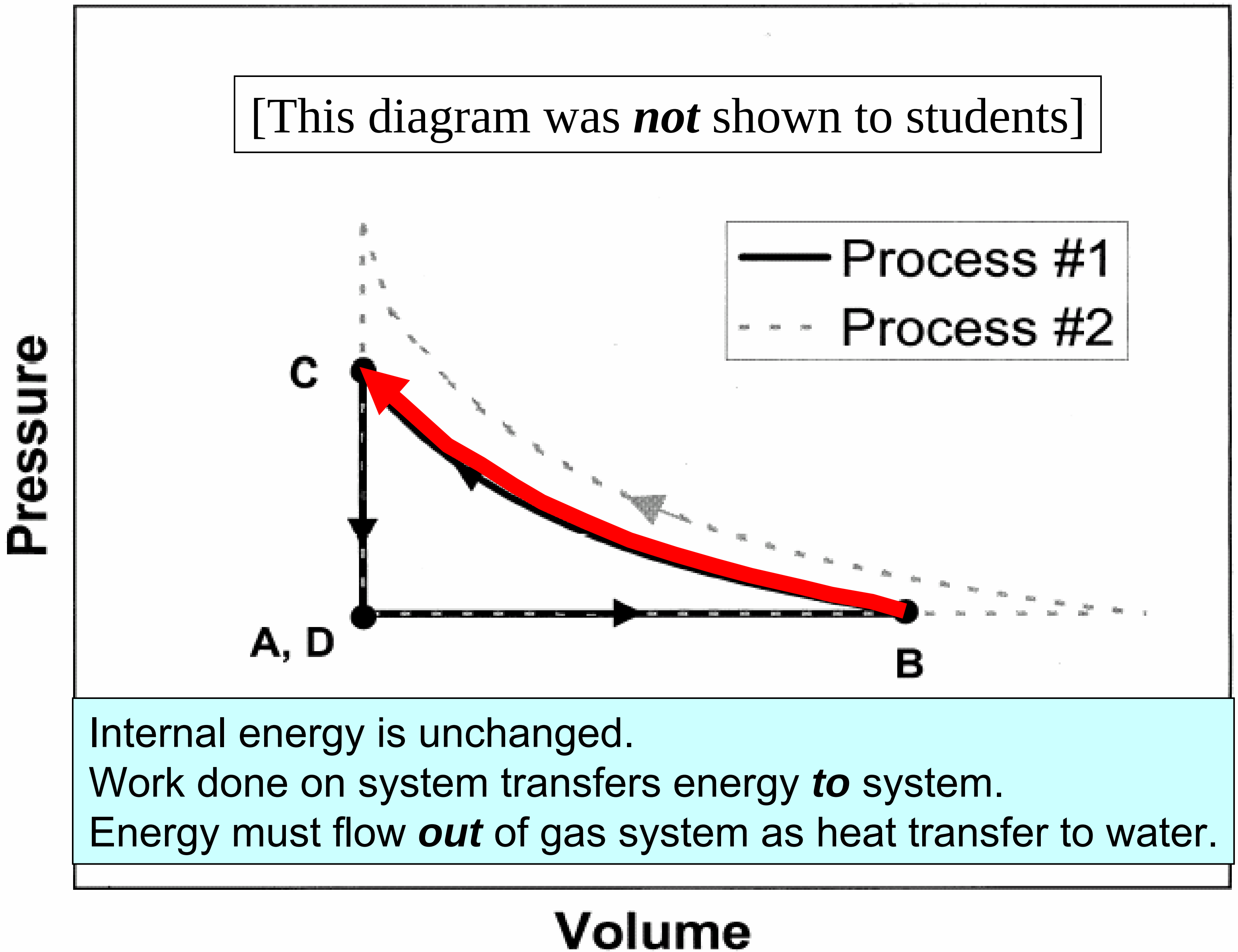


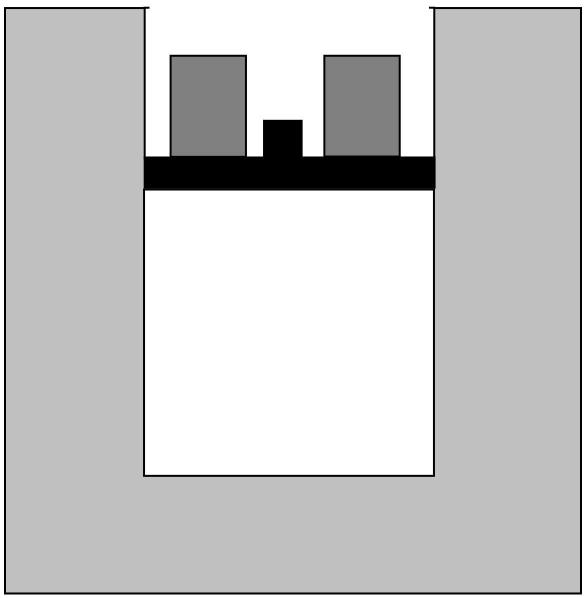
Question #4: During the process that occurs from time *B* to time *C*, is there *any* net energy flow between the gas and the water? If no, explain why not. If yes, is there a net flow of energy from gas to water, or from water to gas?


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

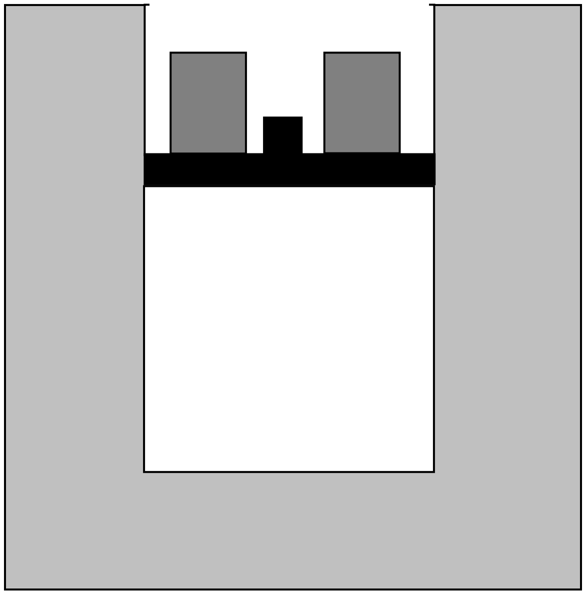

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Internal energy is unchanged.
Pressure
Volume


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


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

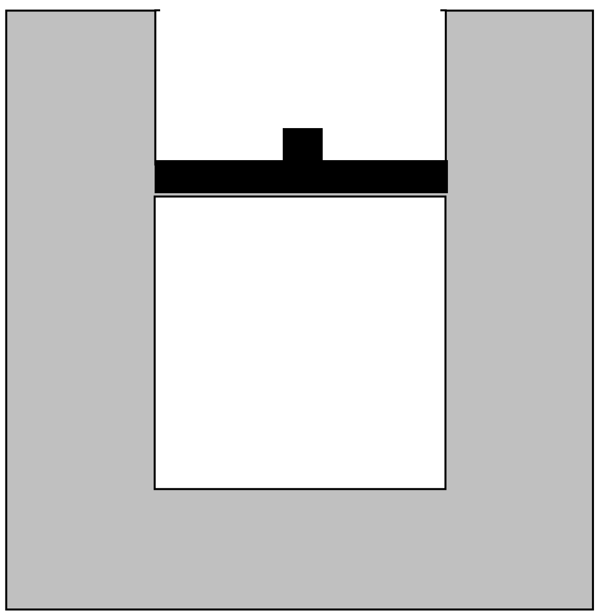
Misunderstanding of "thermal reservoir" concept, in which heat may be transferred to or from an entity that has practically unchanging temperature

Thermal Physics Students Shared Difficulties Manifested by Introductory Students

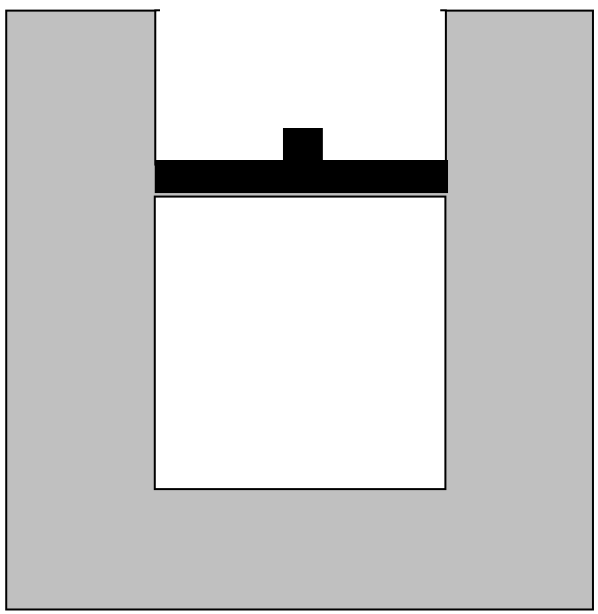
- Failed to recognize that total kinetic energy of ideal gas molecules does ***not*** change when temperature is held constant:
  - **Interview sample: 44%**
  - **2004 Thermal Physics students: 45%**

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

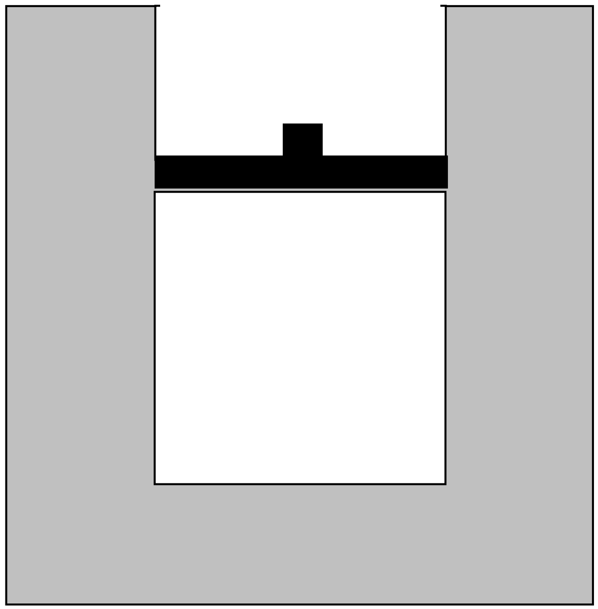
Now, the piston is locked into place so it *cannot move*, and the weights are removed from the piston.



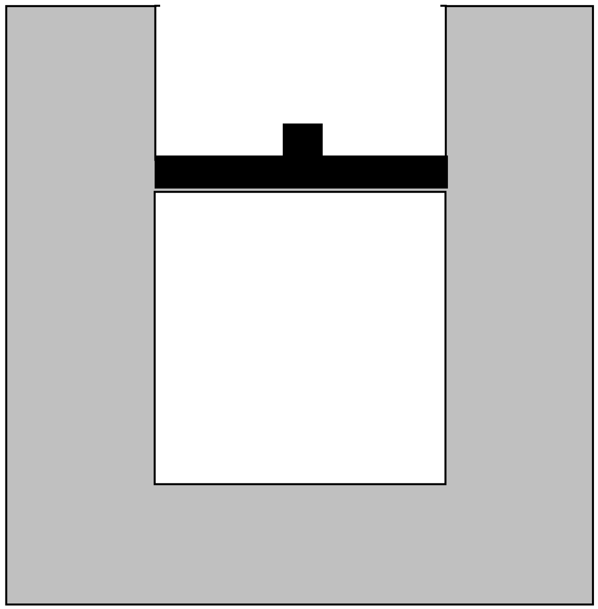
The system is left to sit in the room for many hours.

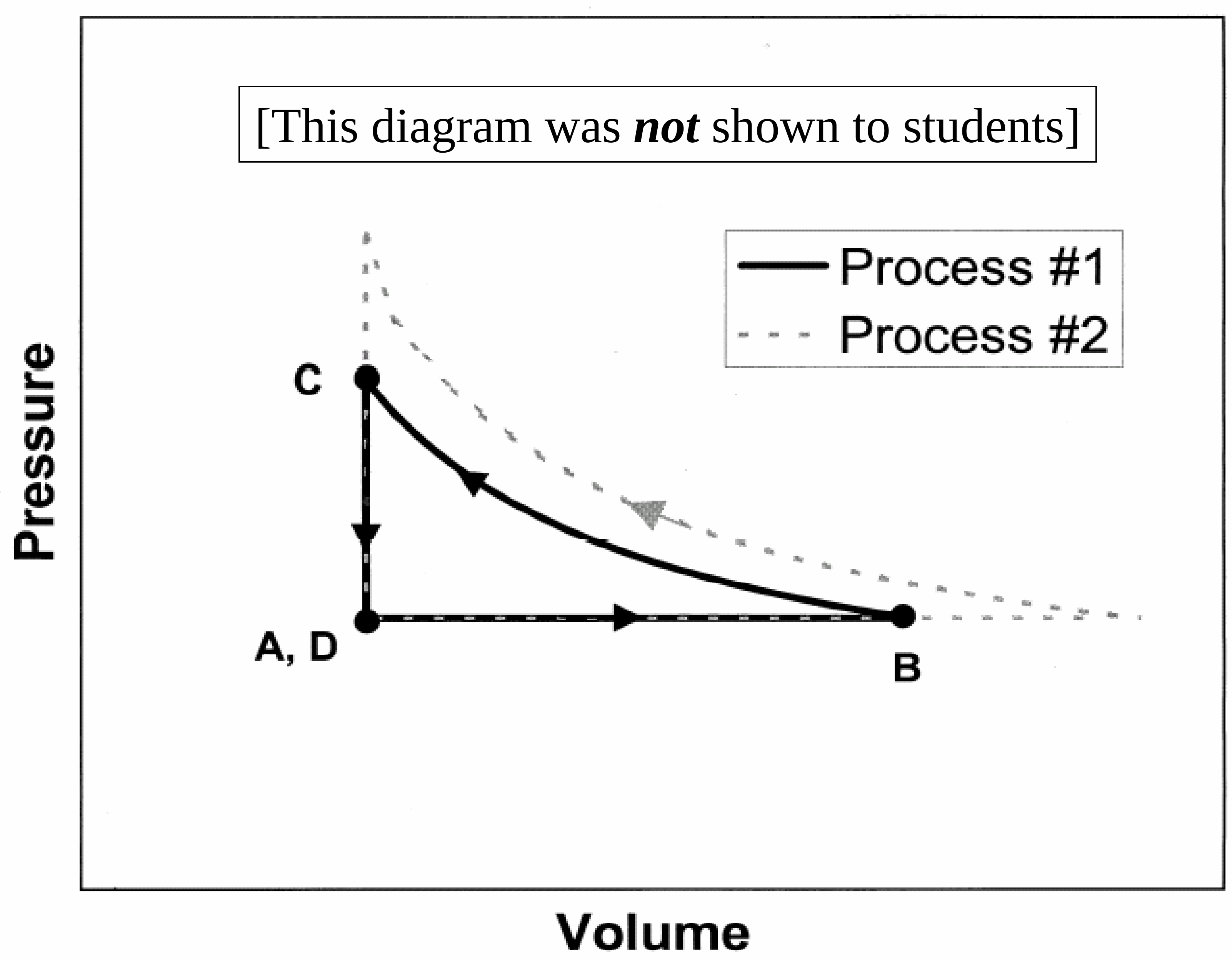


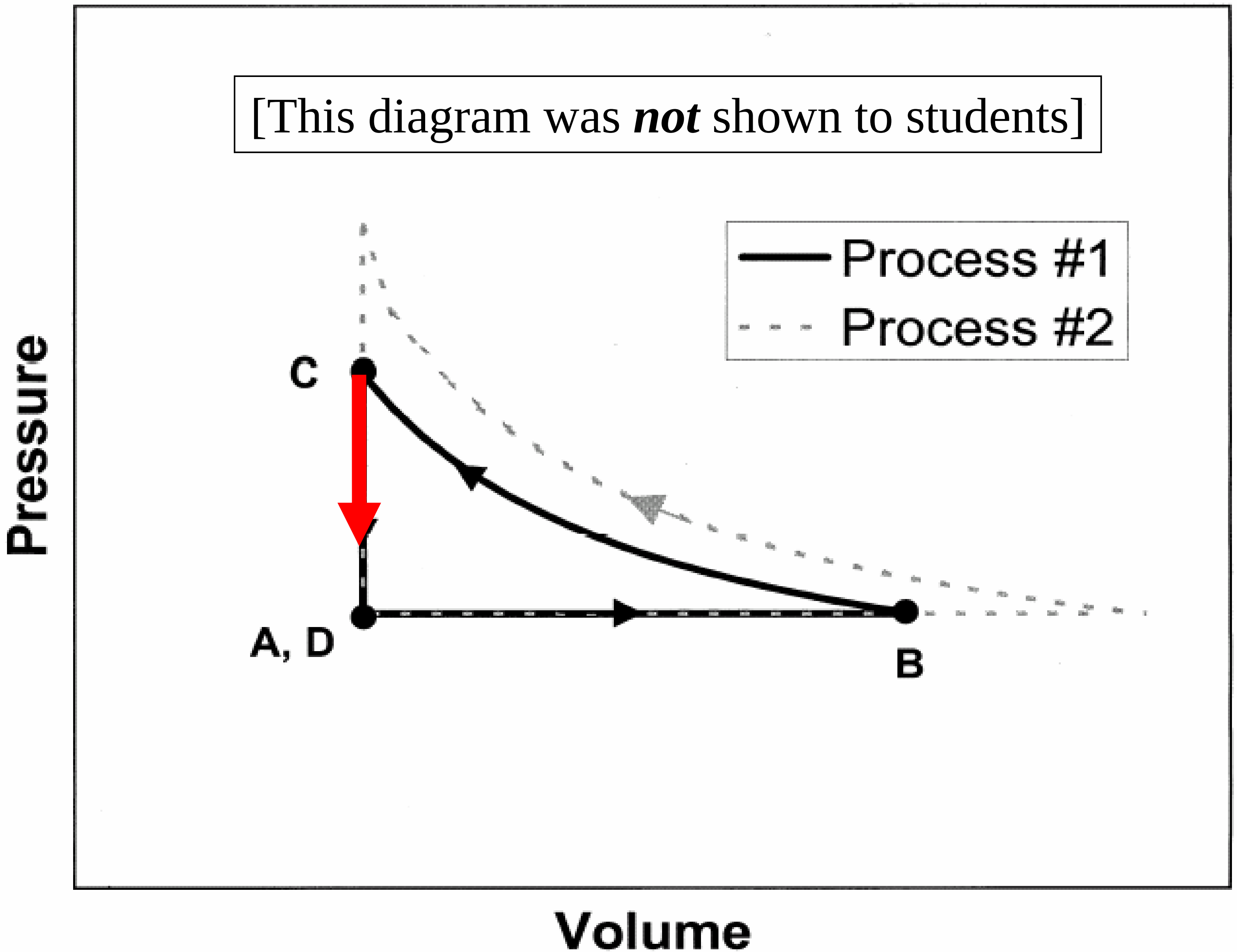
Eventually the entire system cools back down to the same room temperature it had at time ***A***.

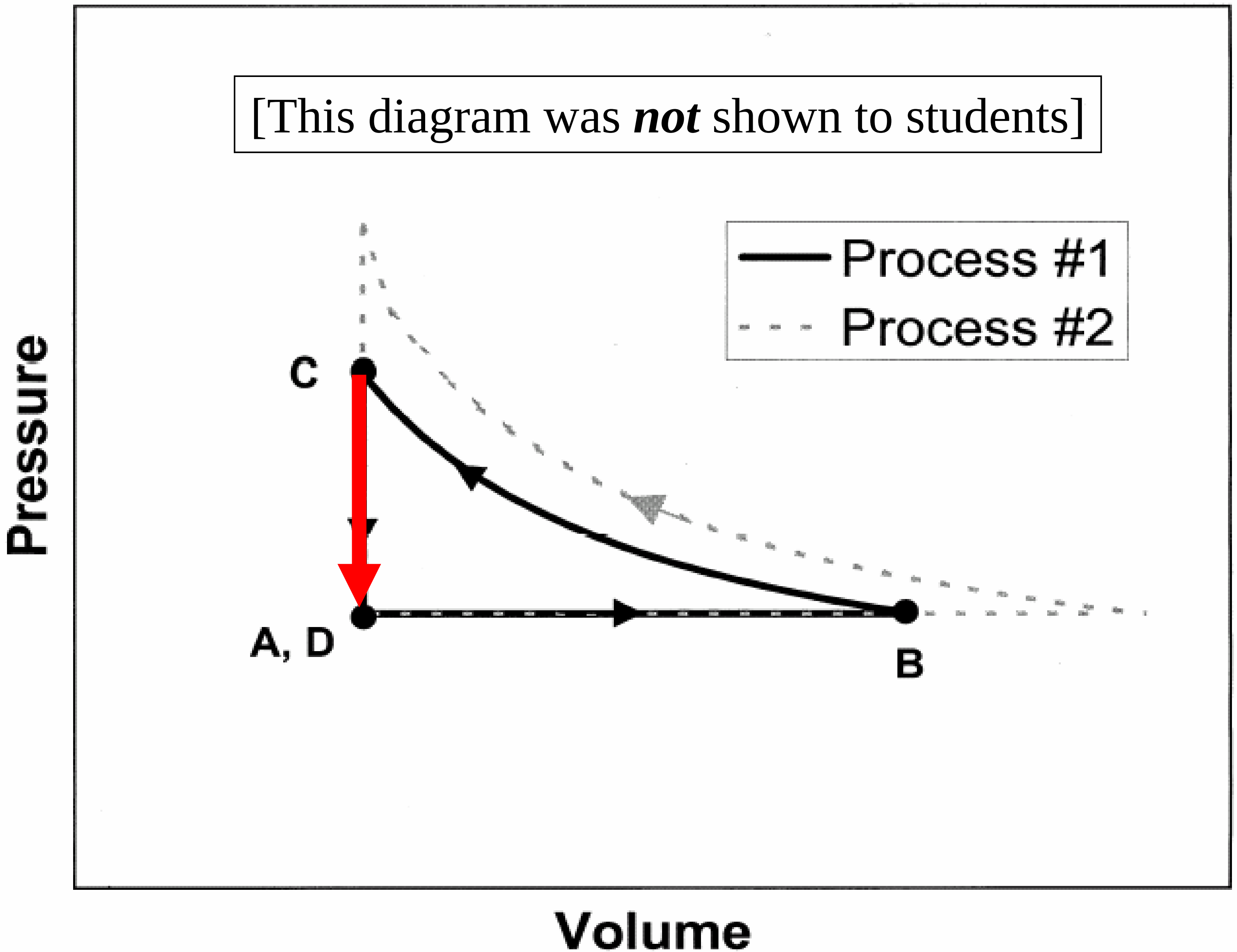


After cooling is complete, it is time ***D.***

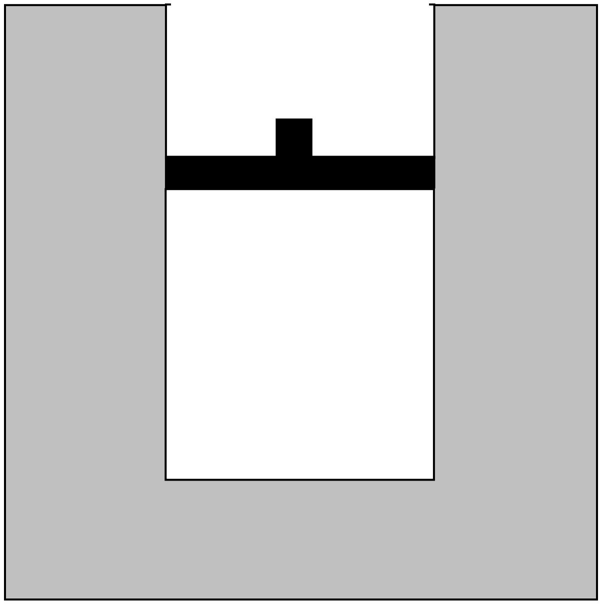



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume


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



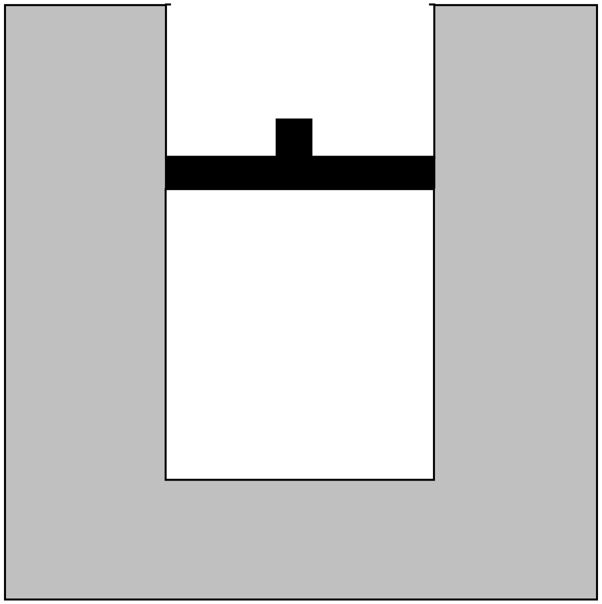
[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



Question #6: Consider ***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?

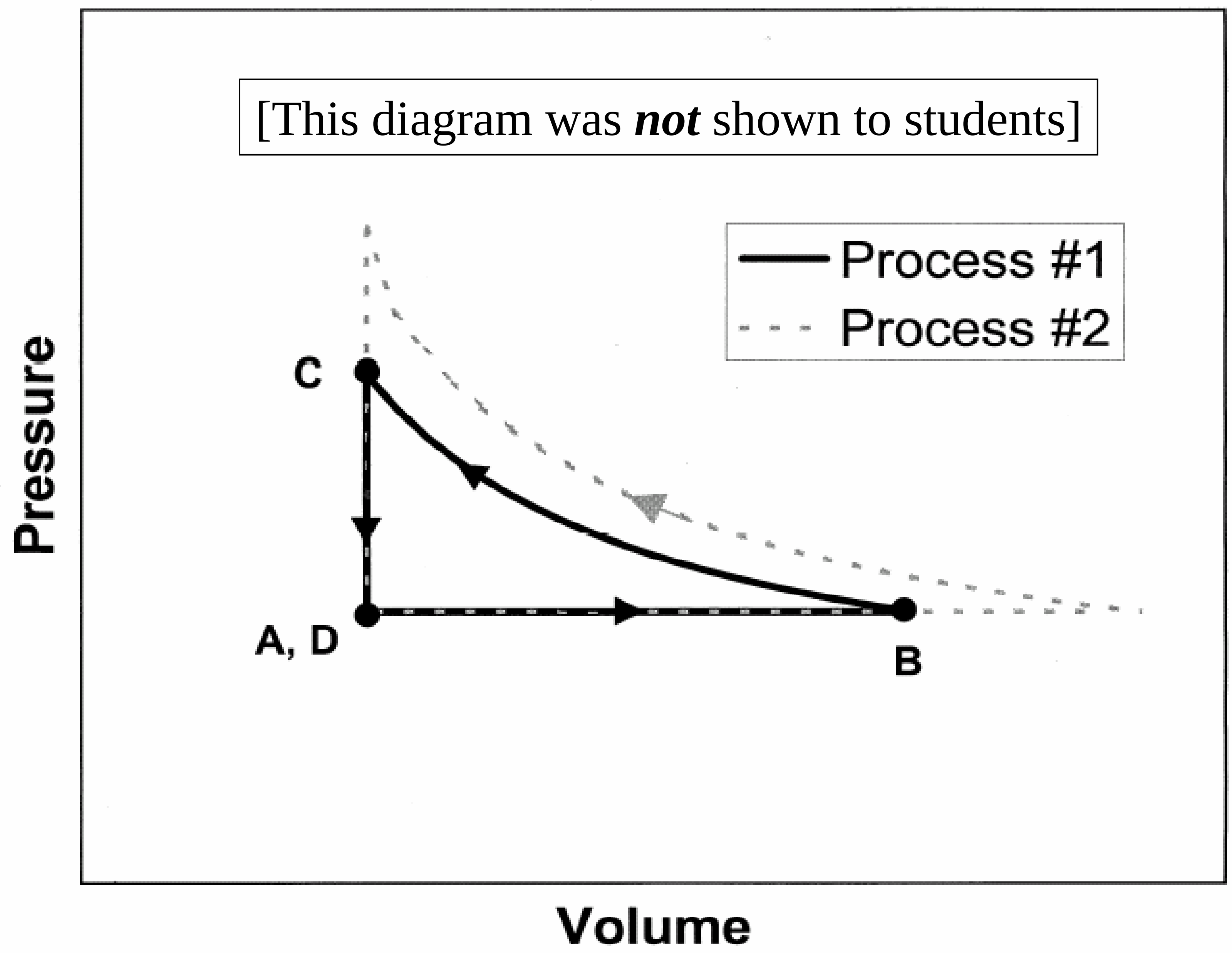
(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

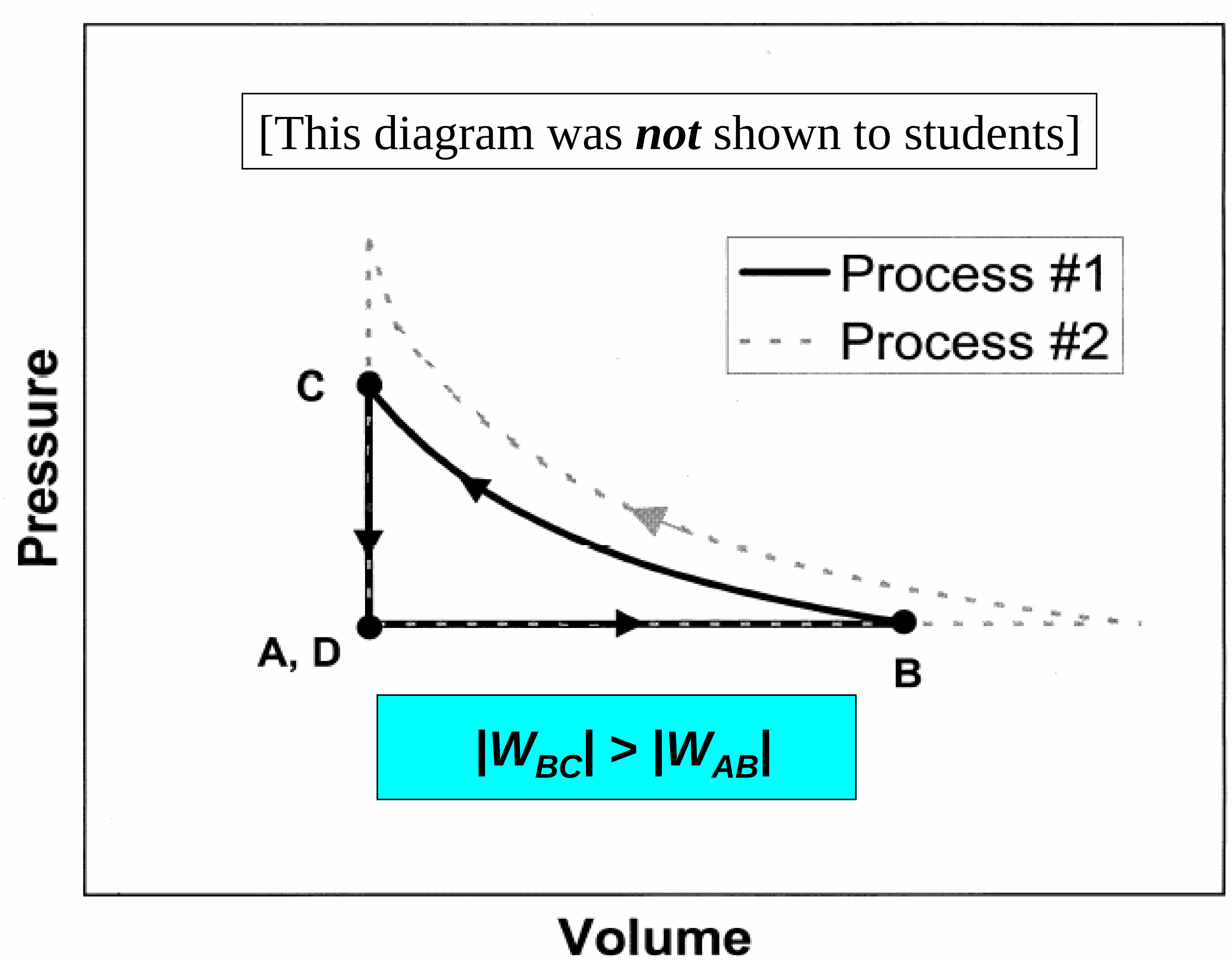


Question #6: Consider ***<u>the entire process</u>*** from time *A* to time *D*.

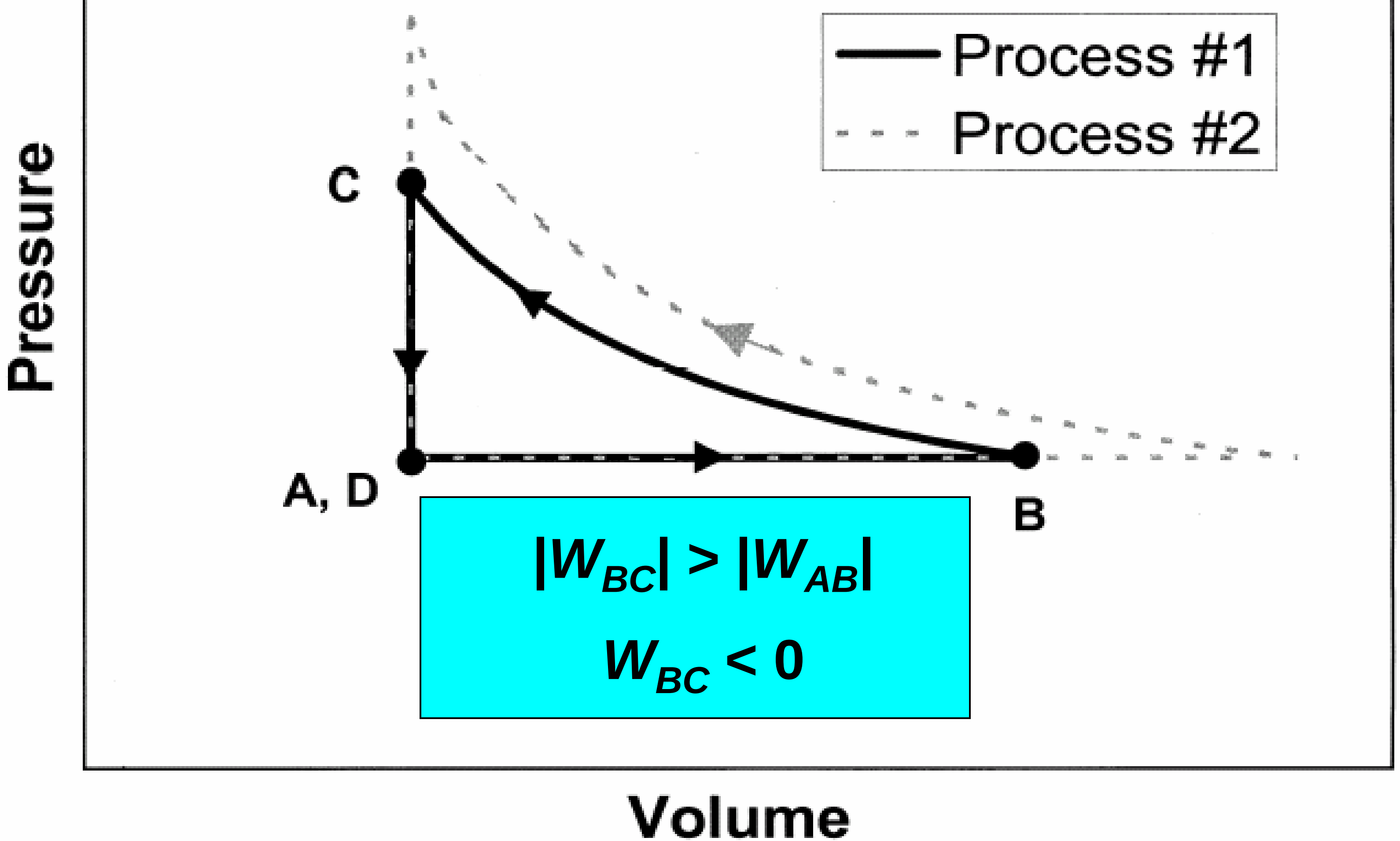
(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

(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

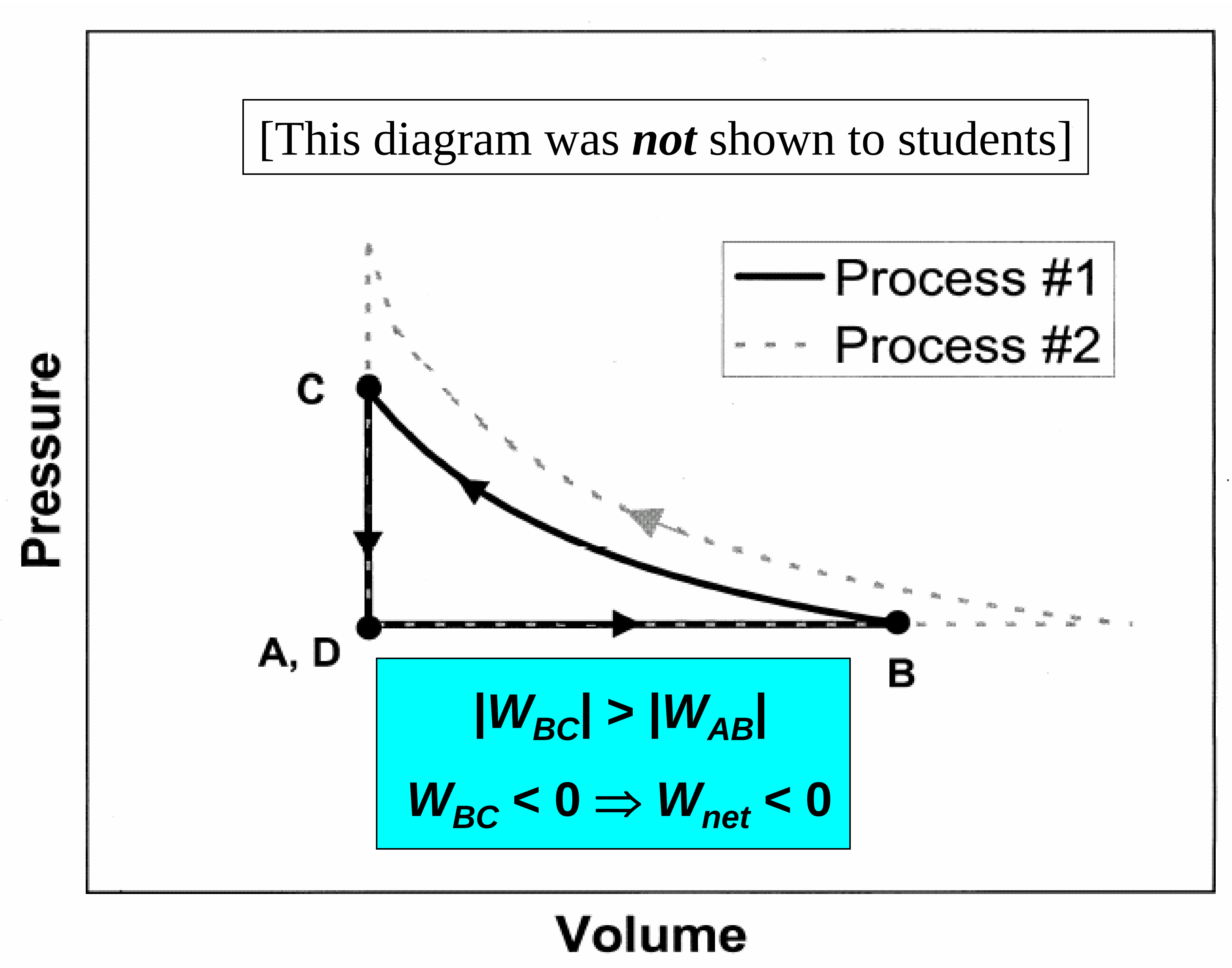

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
|W_BC| > |W_AB|
Pressure
Volume

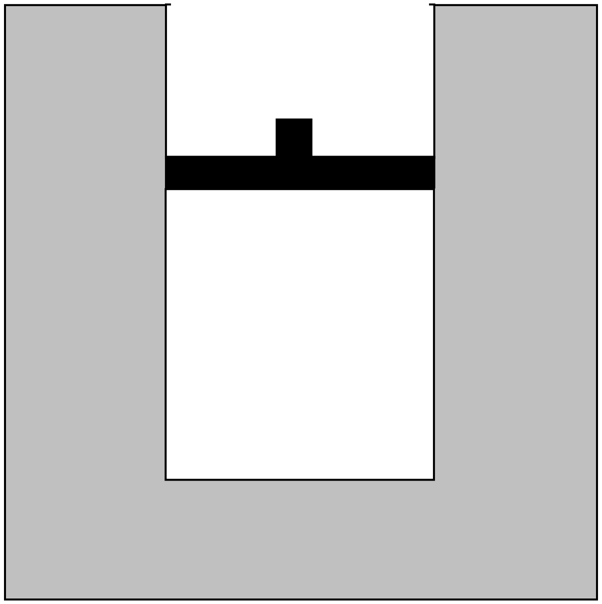
[This diagram was ***not*** shown to students]



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

$W_{BC} < 0$

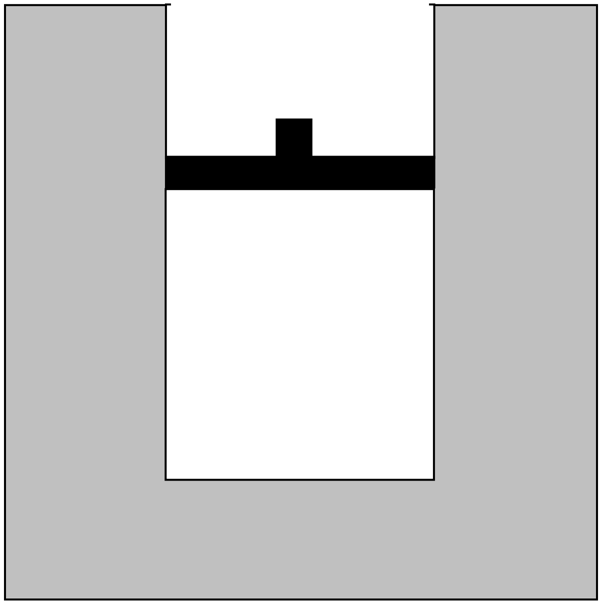

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
$|W_{BC}| > |W_{AB}|$
$W_{BC} < 0 \Rightarrow W_{net} < 0$
Pressure
Volume



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?



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 (i)

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

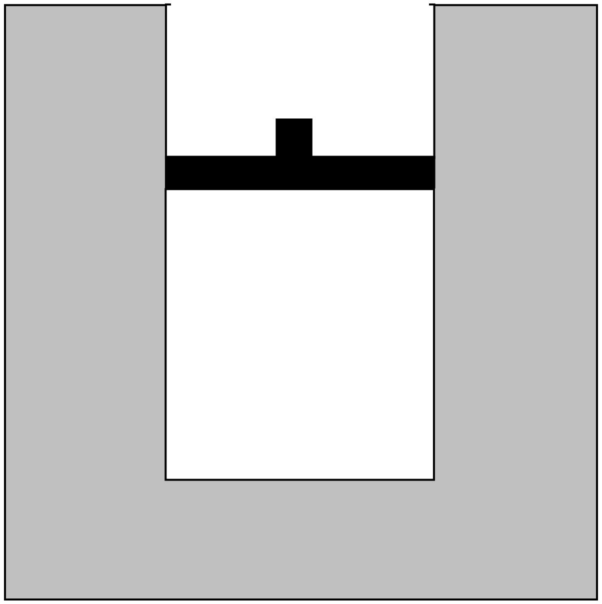
Interview sample *[post-test, N = 32]**: 19%***

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

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

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

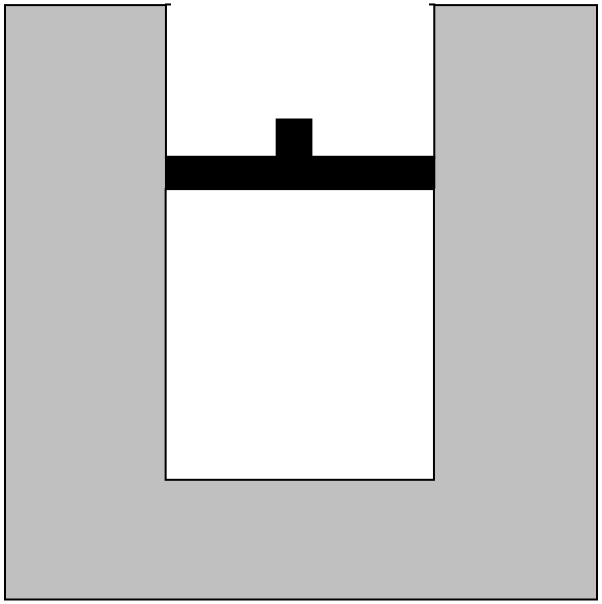
2004 Thermal Physics *[pre-test, N = 16]**: 45%***



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?

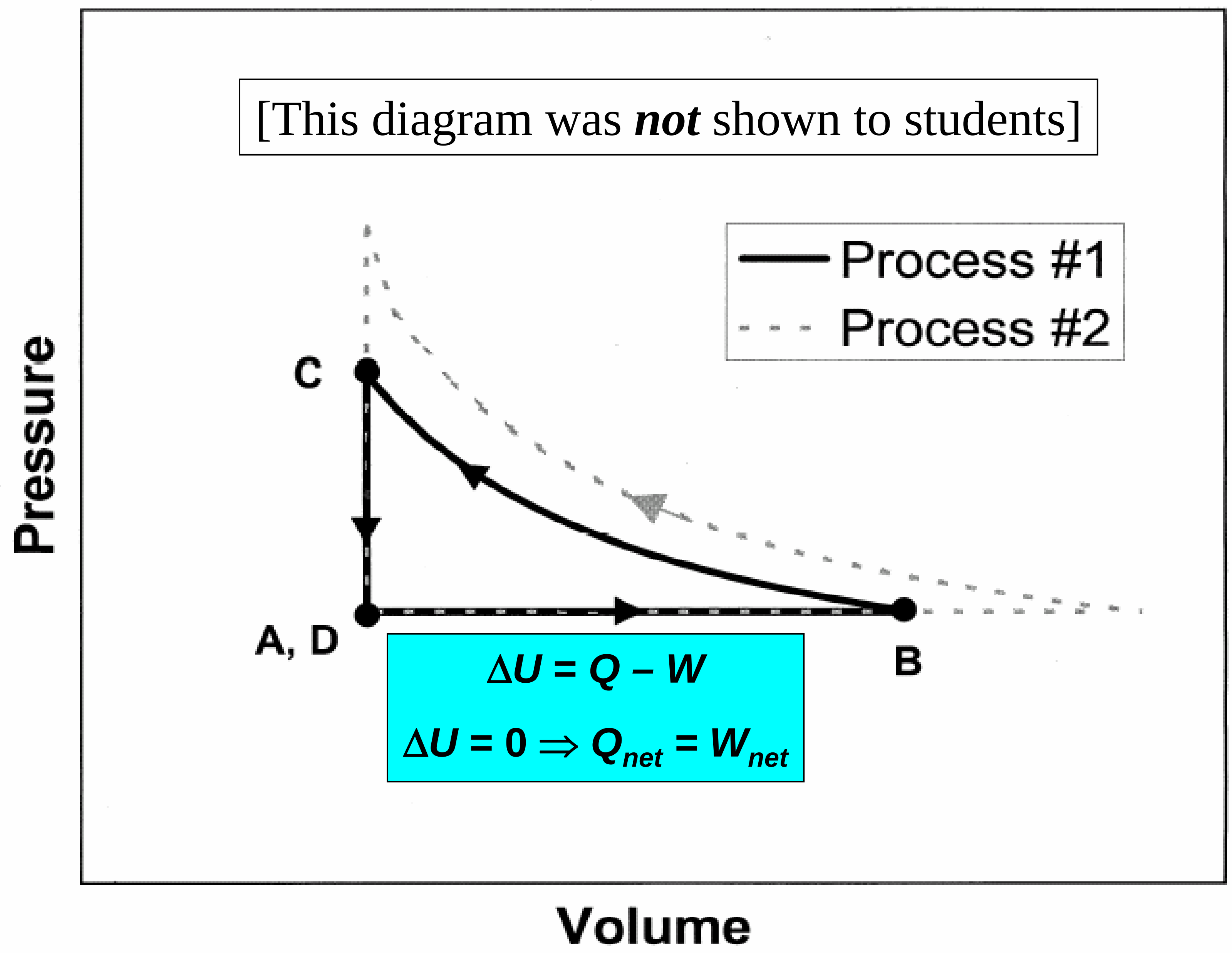
(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?



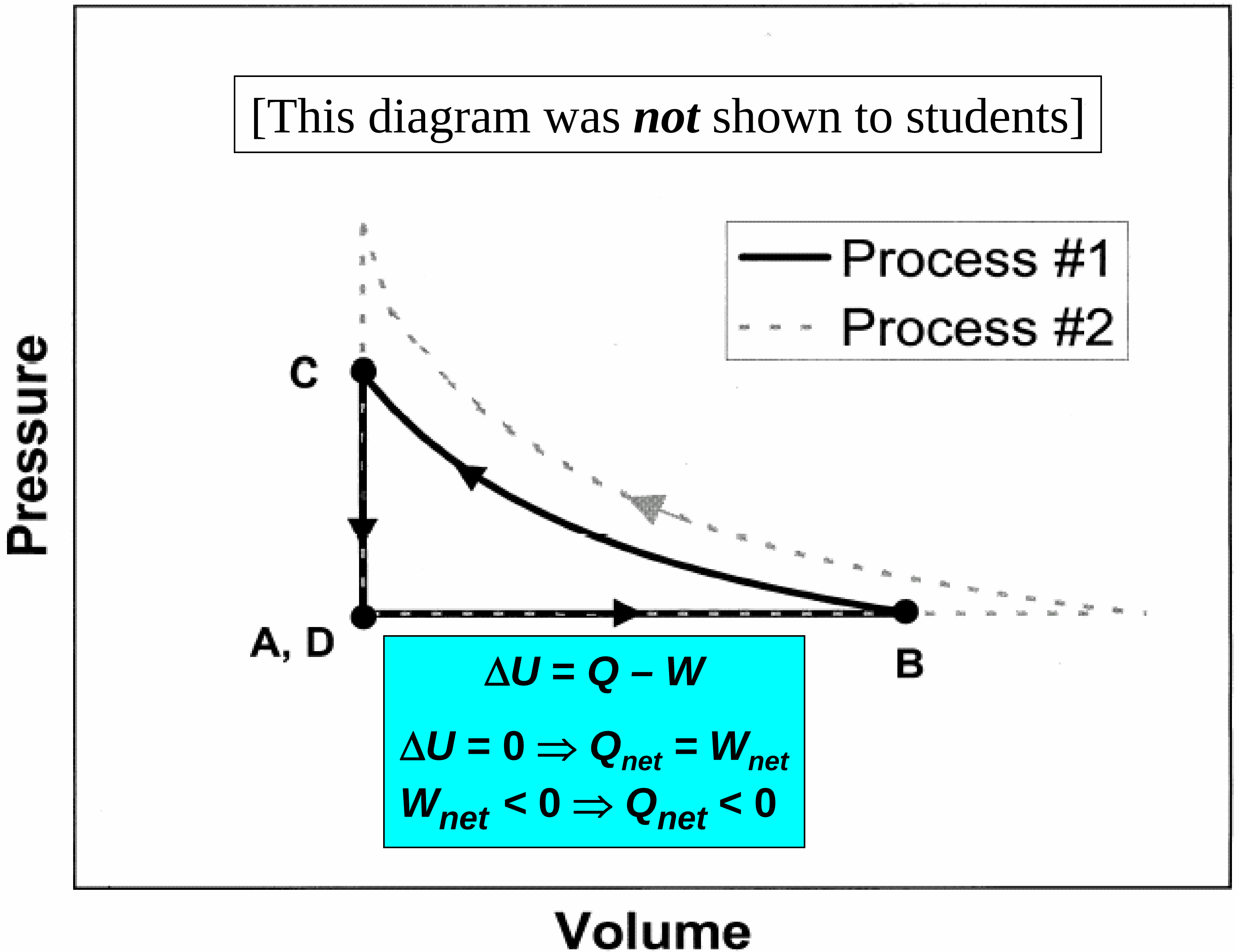
Question #6: Consider ***<u>the entire process</u>*** from time *A* to time *D*.

(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
$\Delta U = Q - W$
$\Delta U = 0 \Rightarrow Q_{net} = W_{net}$
Pressure
Volume

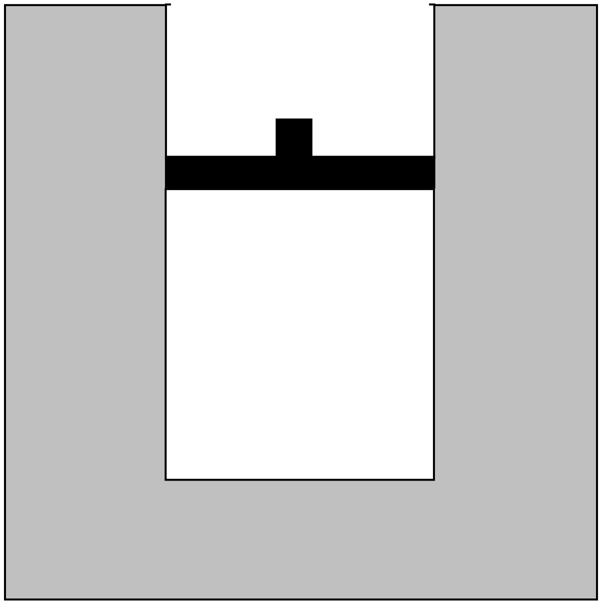
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

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

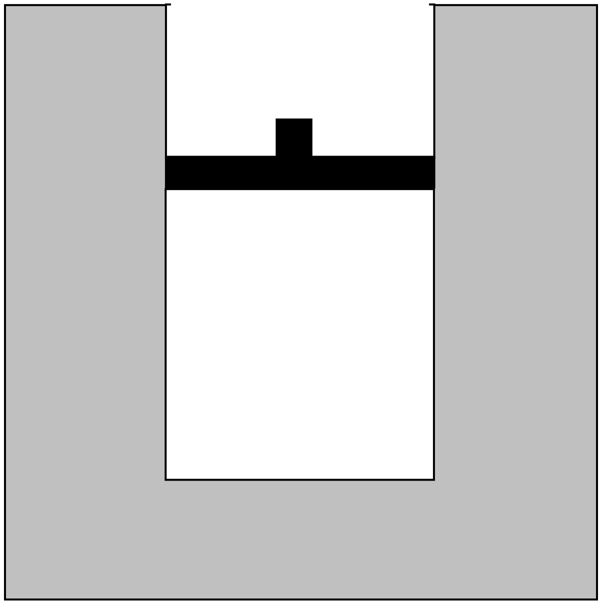
$$W_{net} < 0 \Rightarrow Q_{net} < 0$$



Question #6: Consider ***<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.

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

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

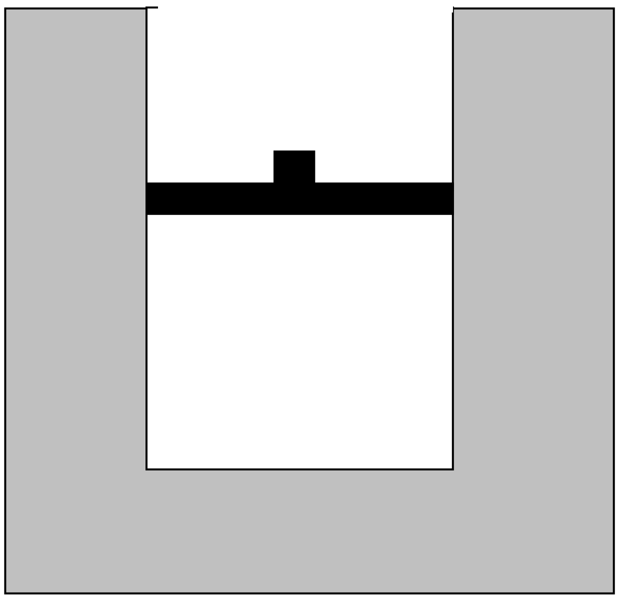
Some Strategies for Instruction

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

Some Strategies for Instruction

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

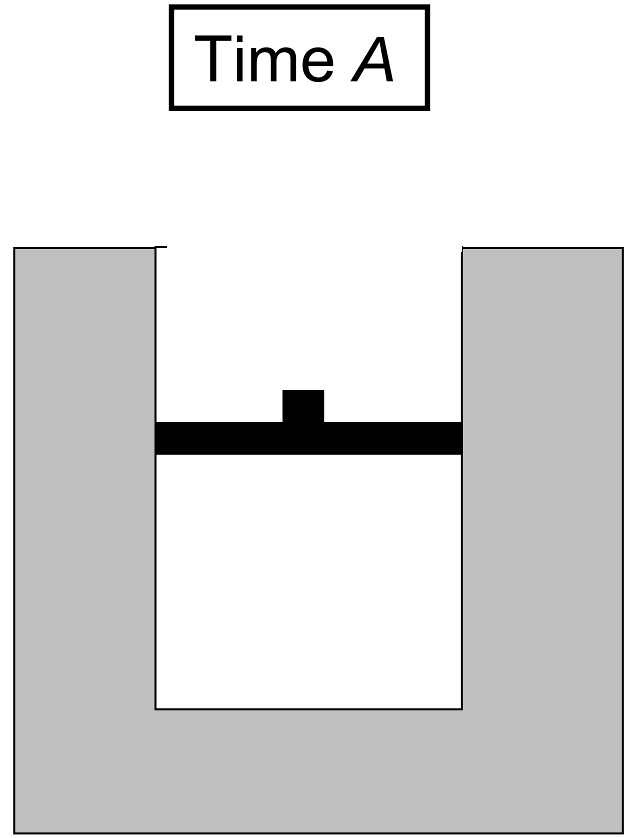
Cyclic Process Worksheet
(adapted from interview questions)



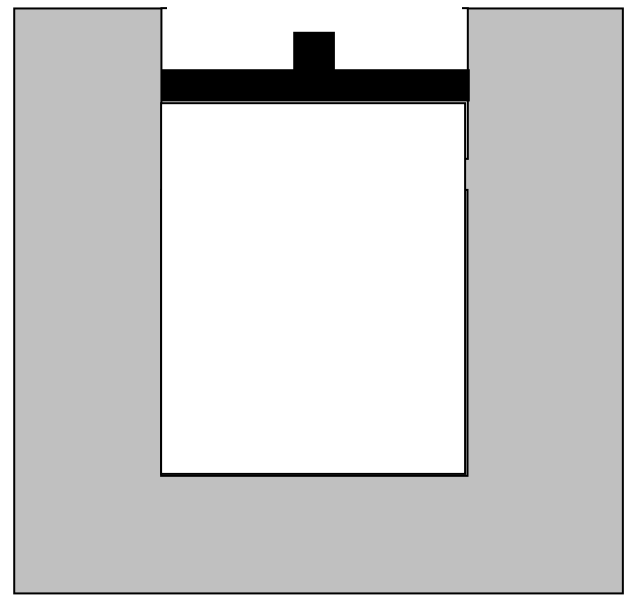
Worksheet Strategy

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

System heated

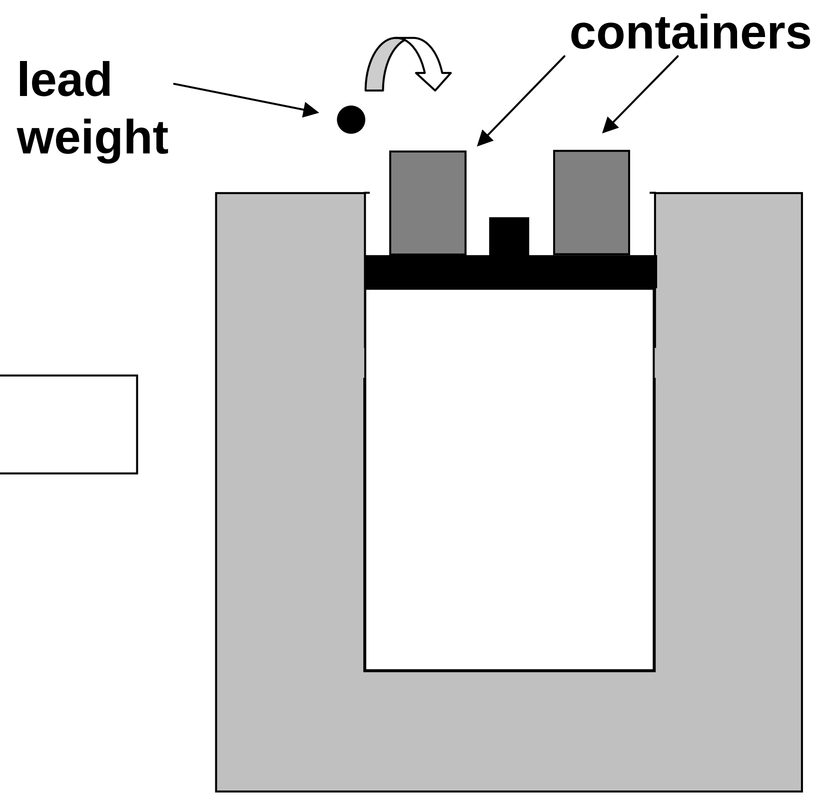


Time *B*



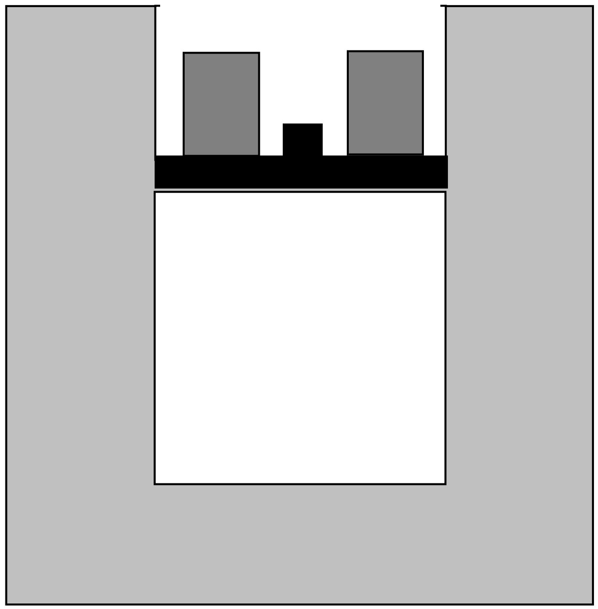
System heated, piston goes up.

Time *B*



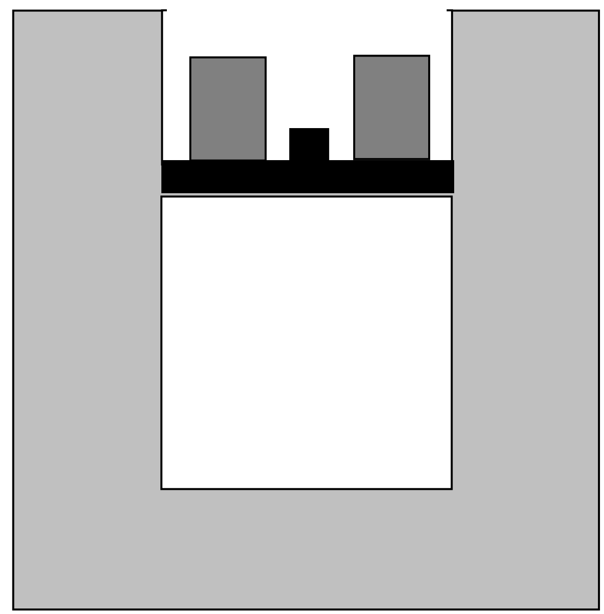
Weights added

Time *C*



Weights added, piston goes down.

Time *C*



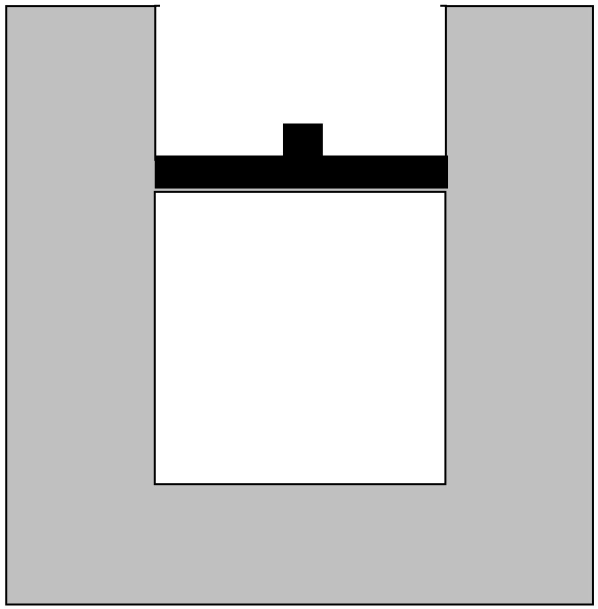
Weights added, piston goes down.

[Temperature remains constant]

Time *C*

Temperature *C*

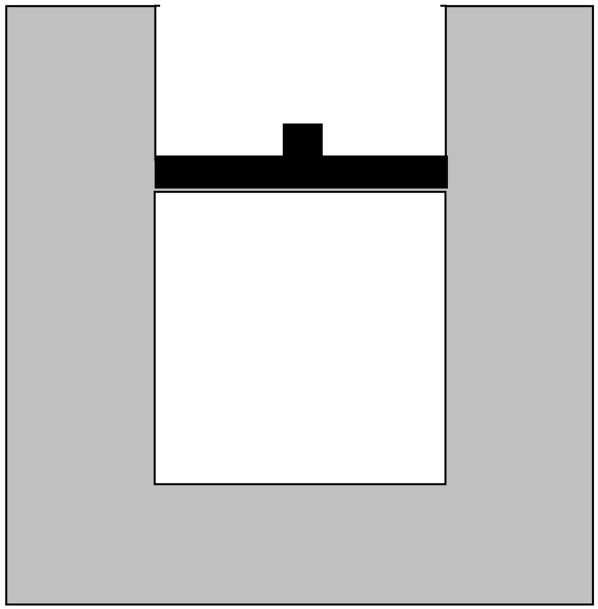
Piston locked

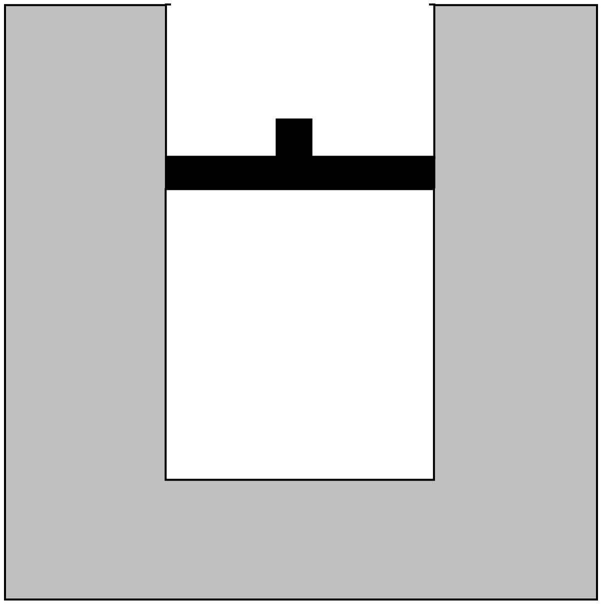


Time *D*

Temperature *D*

Piston locked, temperature goes down.

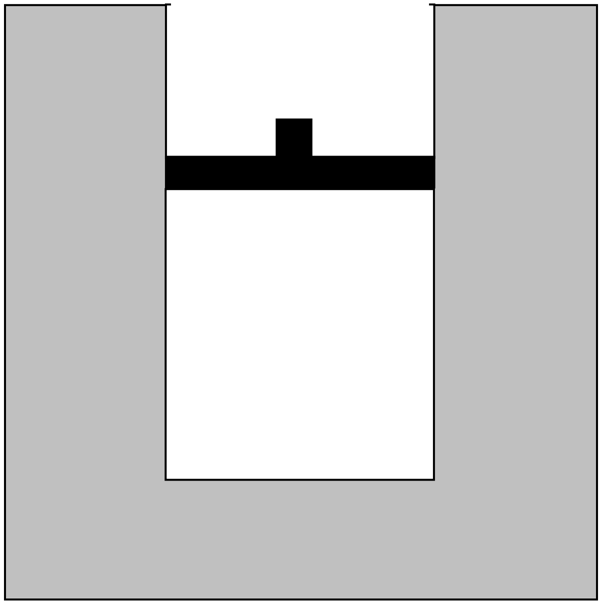




Question #6: Consider ***the entire process*** from time *A* to time *D*.

(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?



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

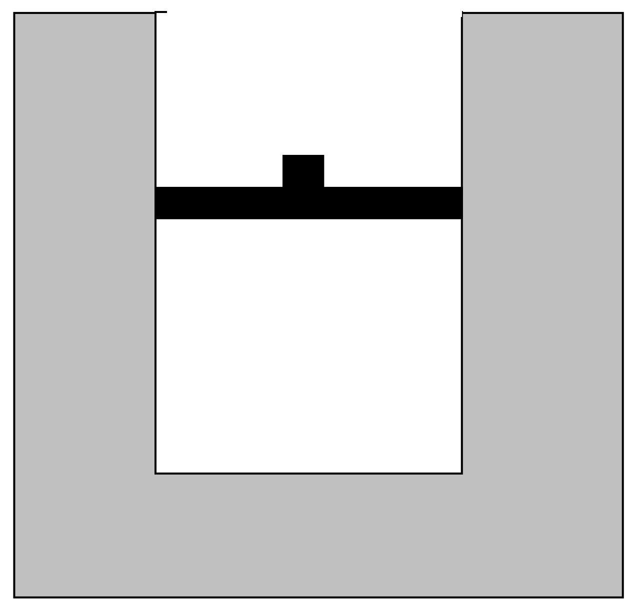
(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

(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?

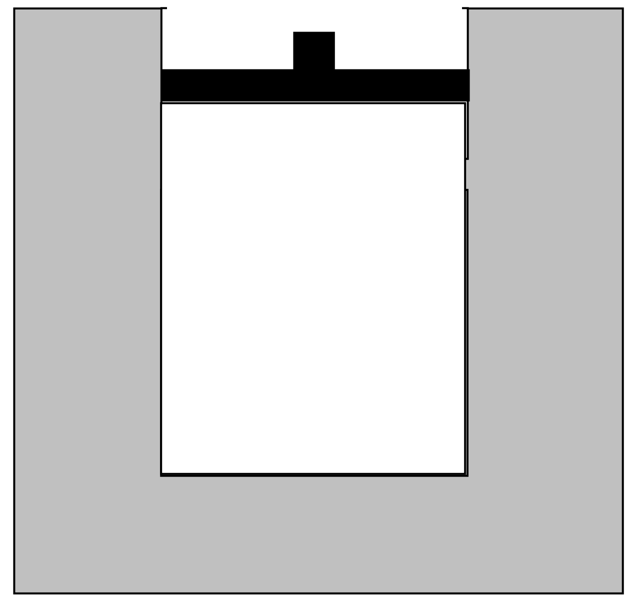
Worksheet Strategy

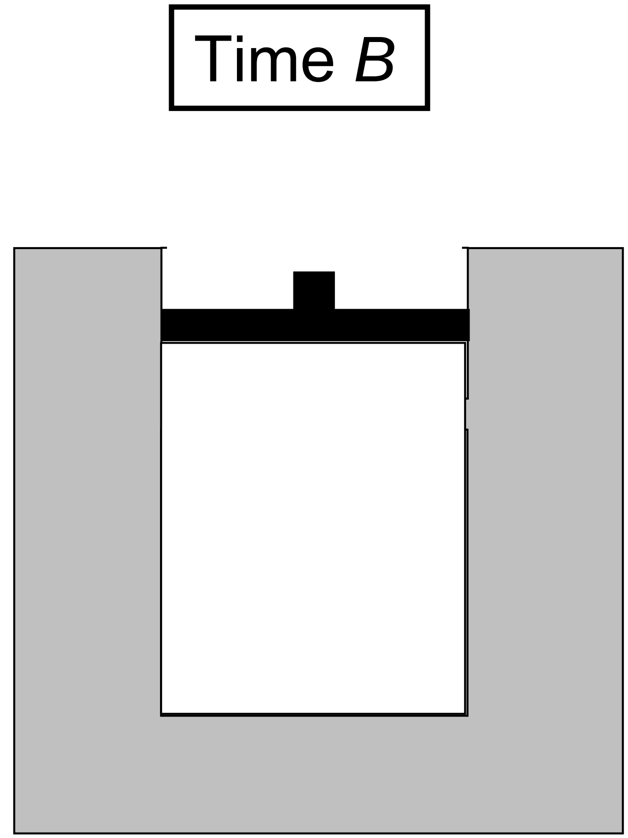
- First, allow students to read description of entire process and answer questions regarding work and heat.
- Then, prompt students for step-by-step responses.

Time *A*



Time *B*

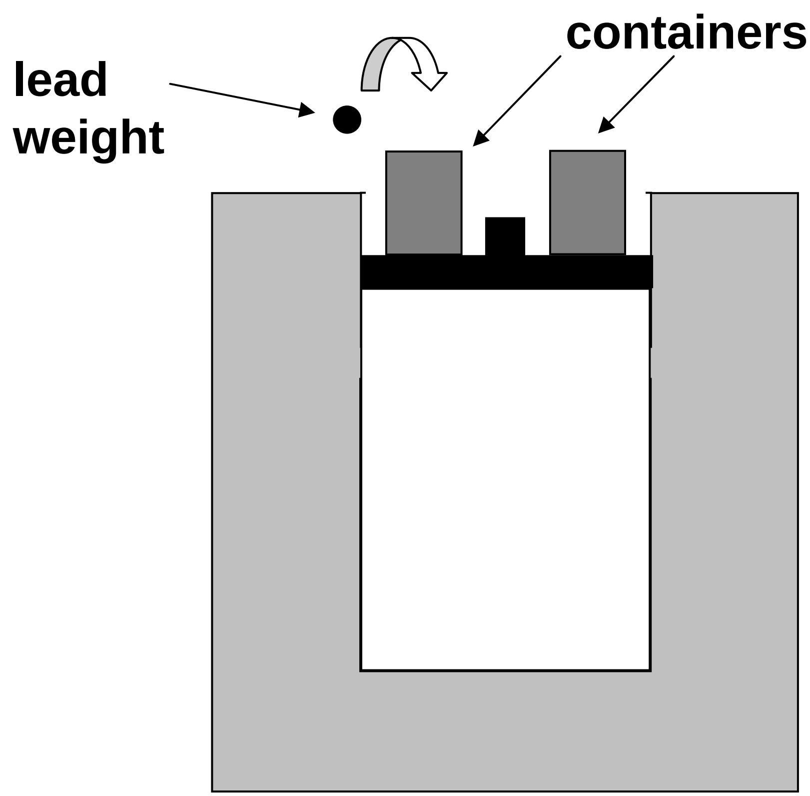




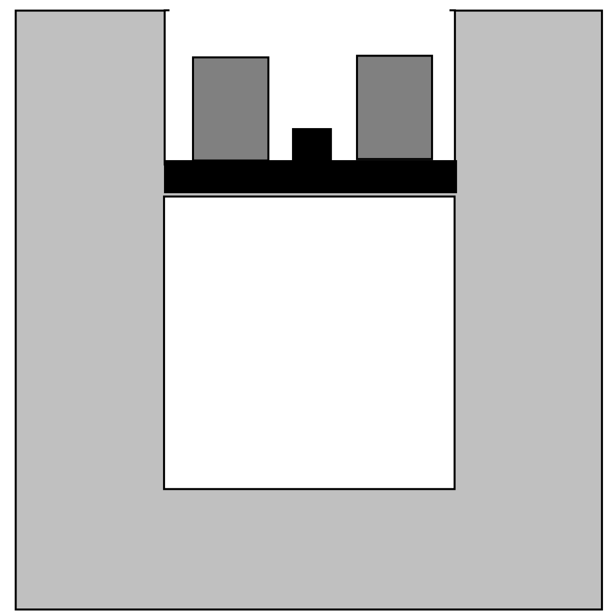
1) For the process A → B, is the work done by the system (W_{AB}) *positive*, *negative*, or *zero*?

Explain your answer.

Time *B*

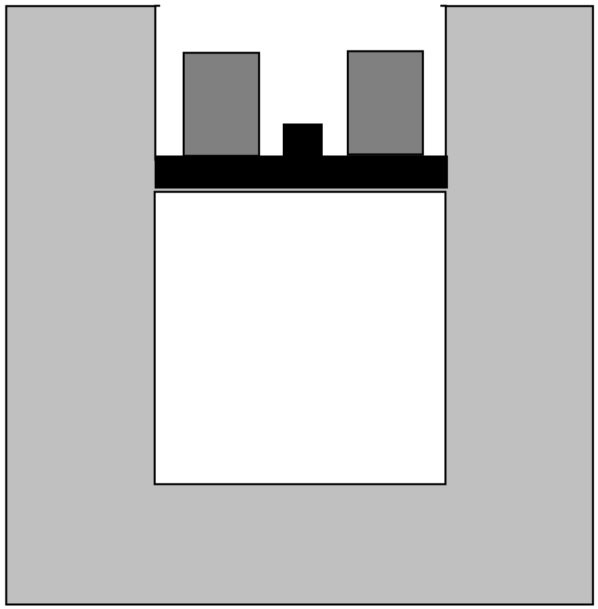


Time *C*



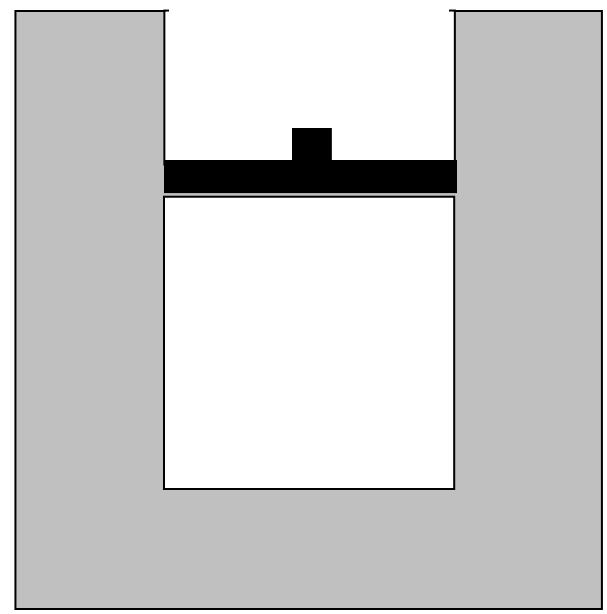
Time C

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



Time *C*

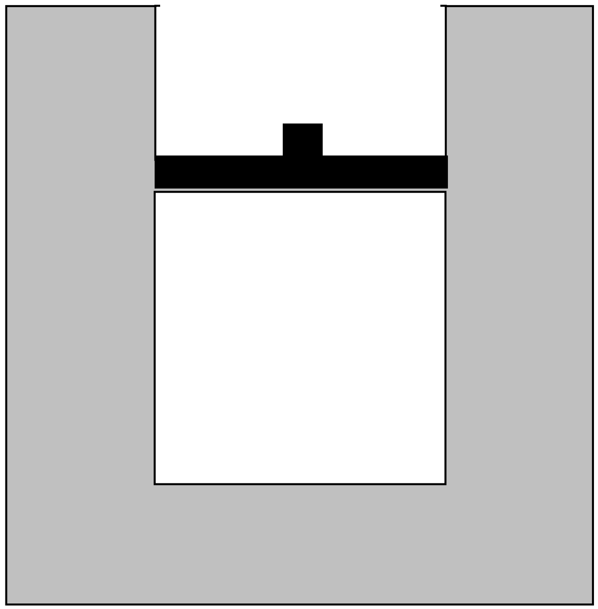
Temperature *C*



Time *D*

Temperature *D*

3) For the process C → D, is the work done by the system (W_{CD}) *positive*, *negative*, or *zero*?



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

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

3) For the process C → D, is the work done by the system (W_{CD}) *positive*, *negative*, or *zero*?

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

largest ____________________________ *smallest*

Explain your reasoning.

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

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

3) For the process C → D, is the work done by the system (W_{CD}) *positive*, *negative*, or *zero*?

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

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

Explain your reasoning.

Worksheet Strategy

- First, allow students to read description of entire process and answer questions regarding work and heat.
- Then, prompt students for step-by-step responses.
- Finally, compare results of the two chains of reasoning.

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

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

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

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

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

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

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

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

ii) Is your answer consistent with the answer you gave for #6 (i)? Explain.

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

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

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

ii) Is your answer consistent with the answer you gave for #6 (i)? Explain.

Entropy and Second-Law Questions

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

Entropy and Second-Law Questions

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

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 $\Delta U = 0$.

Heat-engines and Second-Law Issues

Heat Engines Pretest…

Consider a system composed of a fixed quantity of gas (not necessarily ideal) that undergoes a cyclic process in which the final state is the same as the initial state.

Consider a system composed of a fixed quantity of gas (not necessarily ideal) that undergoes a cyclic process in which the final state is the same as the initial state.

During one particular cyclic process, there is heat transfer to or from the system at only two fixed temperatures: T_{high} and T_{low}

…

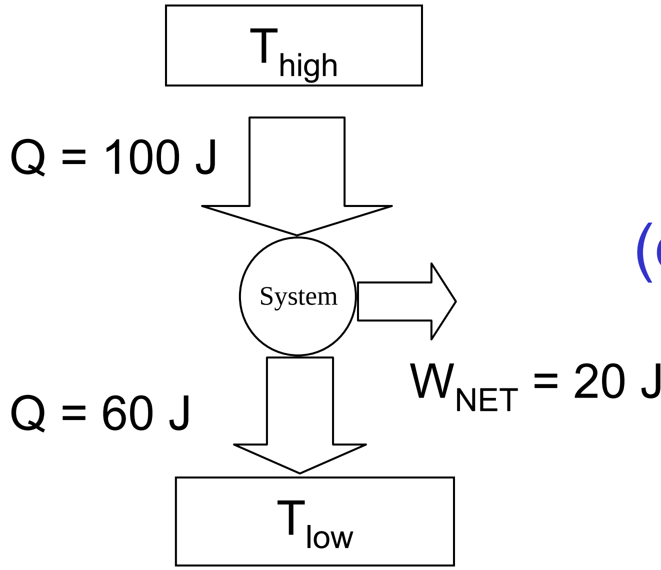
Consider a system composed of a fixed quantity of gas (not necessarily ideal) that undergoes a cyclic process in which the final state is the same as the initial state.

During one particular cyclic process, there is heat transfer to or from the system at only two fixed temperatures: T_{high} and T_{low}

…

For the following processes, state whether they are possible according to the laws of thermodynamics. Justify your reasoning for each question:

heat transfer of 100 J *to* the system at T_{high}
heat transfer of 60 J *away from* the system at T_{low}
net work of 20 J done *by* the system on its surroundings.



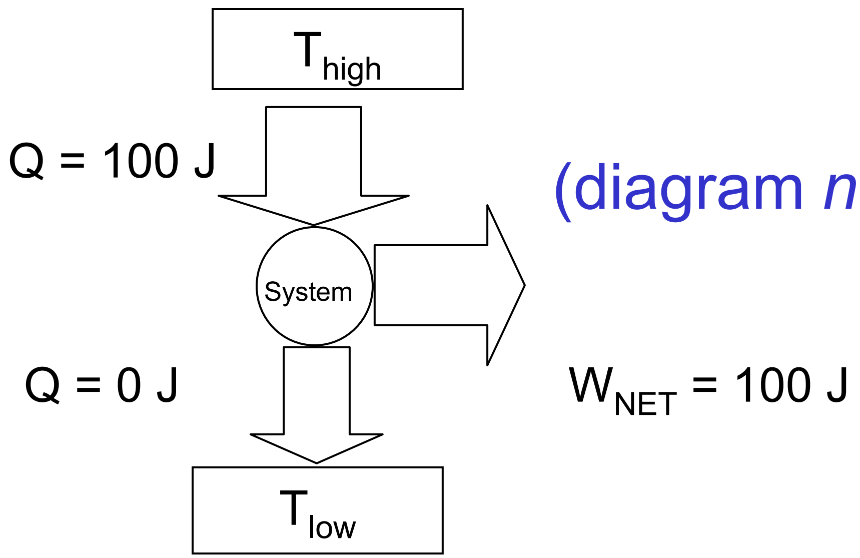
(diagram *not* given)

(violation of first law of thermodynamics)

70% correct (*N* = 17)

heat transfer of 100 J *to* the system at T_{high}
heat transfer of 60 J *away from* the system at T_{low}
net work of 20 J done *by* the system on its surroundings.

heat transfer of 100 J *to* the system at T_{high}
heat transfer of 0 J *away from* the system at T_{low}
net work of 100 J done *by* the system on its surroundings.



(diagram *not* given)

(Perfect heat engine:
violation of second law of thermodynamics)

60% correct (N = 17)

During one particular cyclic process, there is heat transfer to or from the system at only two fixed temperatures: T_{high} and T_{low}. Assume that this process is *reversible*…:

heat transfer of 100 J *to* the system at T_{high}
heat transfer of 60 J *away* from the system at T_{low}
net work of 40 J done *by* the system on its surroundings.

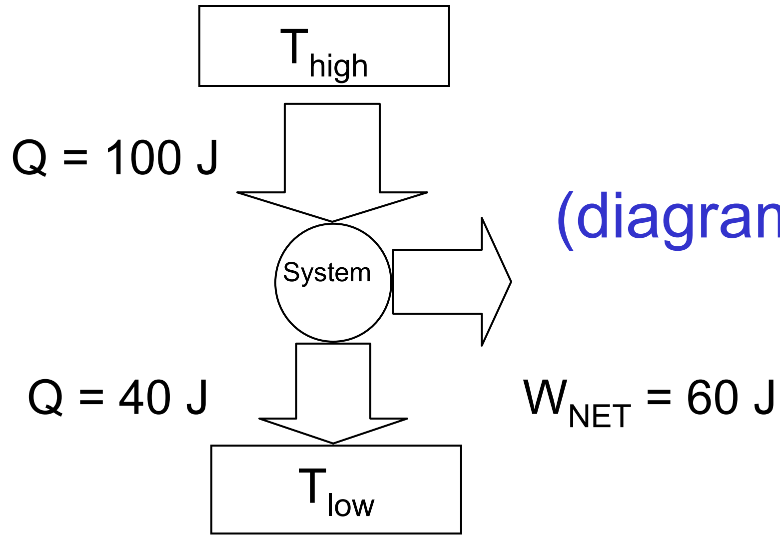
$$\Rightarrow \eta_{reversible} = \frac{W}{Q_{in}} = \frac{40}{100} = 0.40 = \eta_{max}$$

← *Not* given

Now consider a set of processes in which T_{high} and T_{low} have *exactly the same numerical values* as in the example above, but these processes are *not* necessarily reversible.

Now consider a set of processes in which T_{high} and T_{low} have *exactly the same numerical values* as in the example above, but these processes are *not* necessarily reversible. For the following process, state whether it is possible according to the laws of thermodynamics. Justify your reasoning for each question.

heat transfer of 100 J *to* the system at T_{high}
heat transfer of 40 J *away from* the system at T_{low}
net work of 60 J done *by* the system on its surroundings.



(diagram *not* given)

$$\Rightarrow \eta_{process} = \frac{W}{Q_{in}} = \frac{60}{100} = 0.60 > \eta_{reversible}$$ (violation of second law)

0% correct (*N* = 15)

Consistent with results reported by Cochran and Heron (Am. J. Phys., 2006)

Heat Engines: Post-Instruction

- Following extensive instruction on second-law and implications regarding heat engines, graded quiz given as post-test

Heat Engines: Post-Instruction

- Following extensive instruction on second-law and implications regarding heat engines, graded quiz given as **post-test**

Consider the following cyclic processes which are being evaluated for possible use as heat engines.

Consider the following cyclic processes which are being evaluated for possible use as heat engines.

For each process, there is heat transfer *to* the system at T = 400 K, and heat transfer *away from* the system at T = 100 K. There is no heat transfer at any other temperatures.

Consider the following cyclic processes which are being evaluated for possible use as heat engines.

For each process, there is heat transfer *to* the system at T = 400 K, and heat transfer *away from* the system at T = 100 K. There is no heat transfer at any other temperatures.

For each cyclic process, answer the following questions: Is the process a *reversible* process, a process that is *possible but irreversible*, or a process that is *impossible*? Explain. (You might want to consider efficiencies.)

$$\Rightarrow \eta_{Carnot} = 1 - \frac{T_{low}}{T_{high}} = 1 - \frac{100}{400} = 0.75 = \eta_{reversible} = \eta_{max}$$

← *Not* given

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

Cycle 2:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

Cycle 3:
heat transfer at high temperature is 200 J;
heat transfer at low temperature is 50 J

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

Cycle 2:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

Cycle 3:
heat transfer at high temperature is 200 J;
heat transfer at low temperature is 50 J

Cycle 2:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

$$\eta_{process} = \frac{W}{Q_{in}}$$

$$\eta_{process} = \frac{W}{Q_{in}} = \frac{Q_{in} - |Q_{out}|}{Q_{in}} = 1 - \frac{|Q_{out}|}{Q_{in}}$$

$$= 1 - \frac{|Q_{low-T}|}{Q_{high-T}}$$

Cycle 2:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

$$\Rightarrow \eta_{process} = 1 - \frac{|Q_{low-T}|}{Q_{high-T}} = 1 - \frac{60}{300} = 0.80 > \eta_{reversible} = \eta_{max}$$

Process is *impossible*

60% correct with correct explanation (*N* = 15)

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

Cycle 2:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

Cycle 3:
heat transfer at high temperature is 200 J;
heat transfer at low temperature is 50 J

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

$$\Rightarrow \eta_{process} = 1 - \frac{|Q_{low-T}|}{Q_{high-T}} = 1 - \frac{100}{300} = 0.67 < \eta_{reversible} = \eta_{max}$$

Process is *possible but irreversible*

55% correct with correct explanation (*N* = 15)

Cycle 1:

heat transfer at high temperature is 300 J;

heat transfer at low temperature is 100 J

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

At the *end* of the process, is the entropy of the system *larger than*, *smaller than*, or *equal to* its value at the *beginning* of the process?

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

At the *end* of the process, is the entropy of the system *larger than*, *smaller than*, or *equal to* its value at the *beginning* of the process?

Answer: $\Delta S_{system} = 0$ since process is cyclic, and *S* is a state function

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

At the *end* of the process, is the entropy of the system *larger than*, *smaller than*, or ***equal to*** its value at the *beginning* of the process?

Answer: $\Delta S_{system} = 0$ since process is cyclic, and *S* is a state function

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

At the *end* of the process, is the entropy of the system *larger than*, *smaller than*, or ***equal to*** its value at the *beginning* of the process?

Answer: $\Delta S_{system} = 0$ since process is cyclic, and S is a state function

40% correct with correct explanation ($N = 15$)

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

At the *end* of the process, is the entropy of the system *larger than*, *smaller than*, or *equal to* its value at the *beginning* of the process?

Most common error: Assume $\Delta S_{system} = \sum_i \frac{Q_i}{T_i}$

(forgetting that this equation requires $Q_{\text{reversible}}$ and this is *not* a reversible process)

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
- “Spontaneous-process” question

Spontaneous Process Question

[Introductory-Course Version]

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

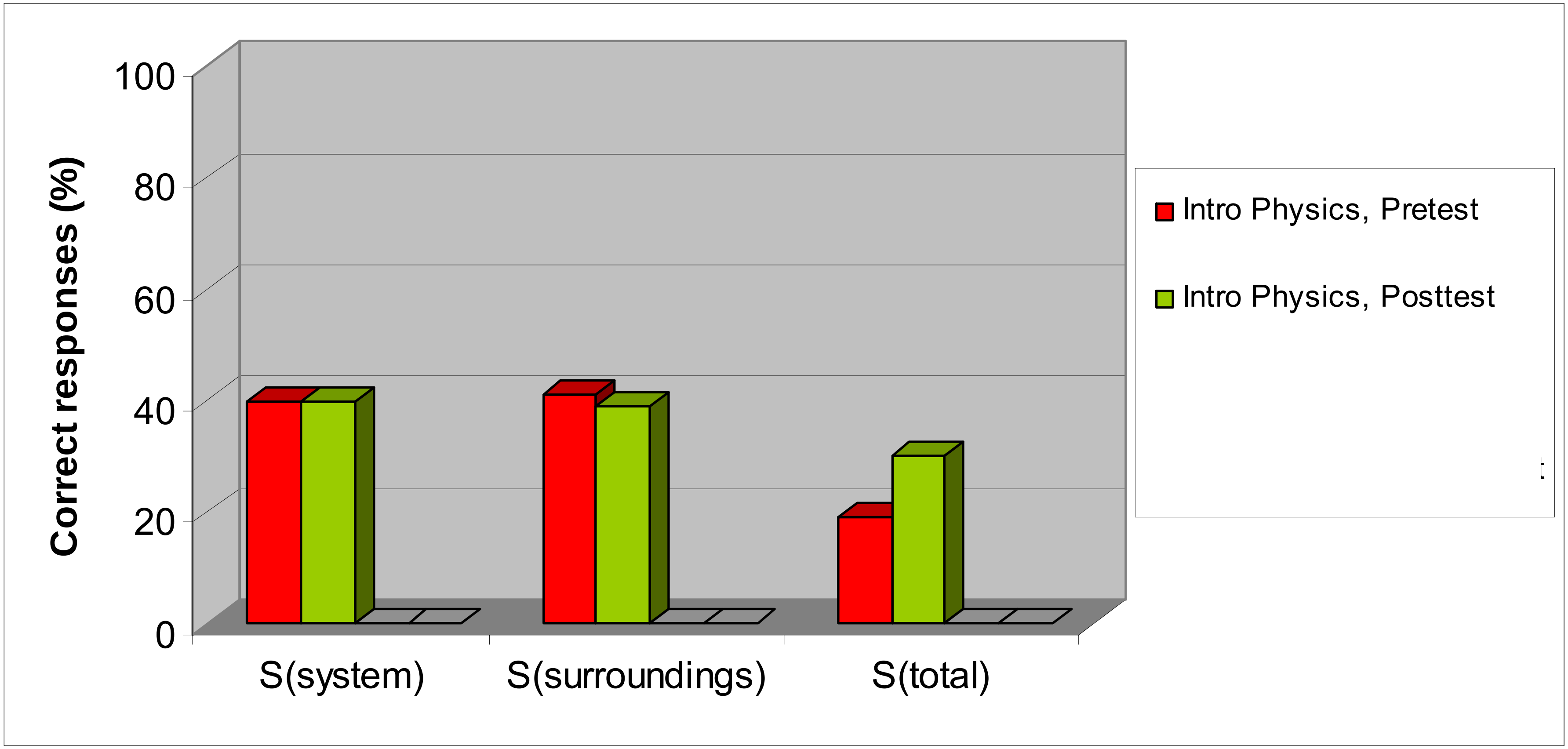
A. During this process, does the entropy of the **<u>system</u>** [S_{system}] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

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

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

Responses to Spontaneous-Process Questions

Introductory Students



Less than 40% correct on each question

Introductory Physics Students' Thinking on Spontaneous Processes

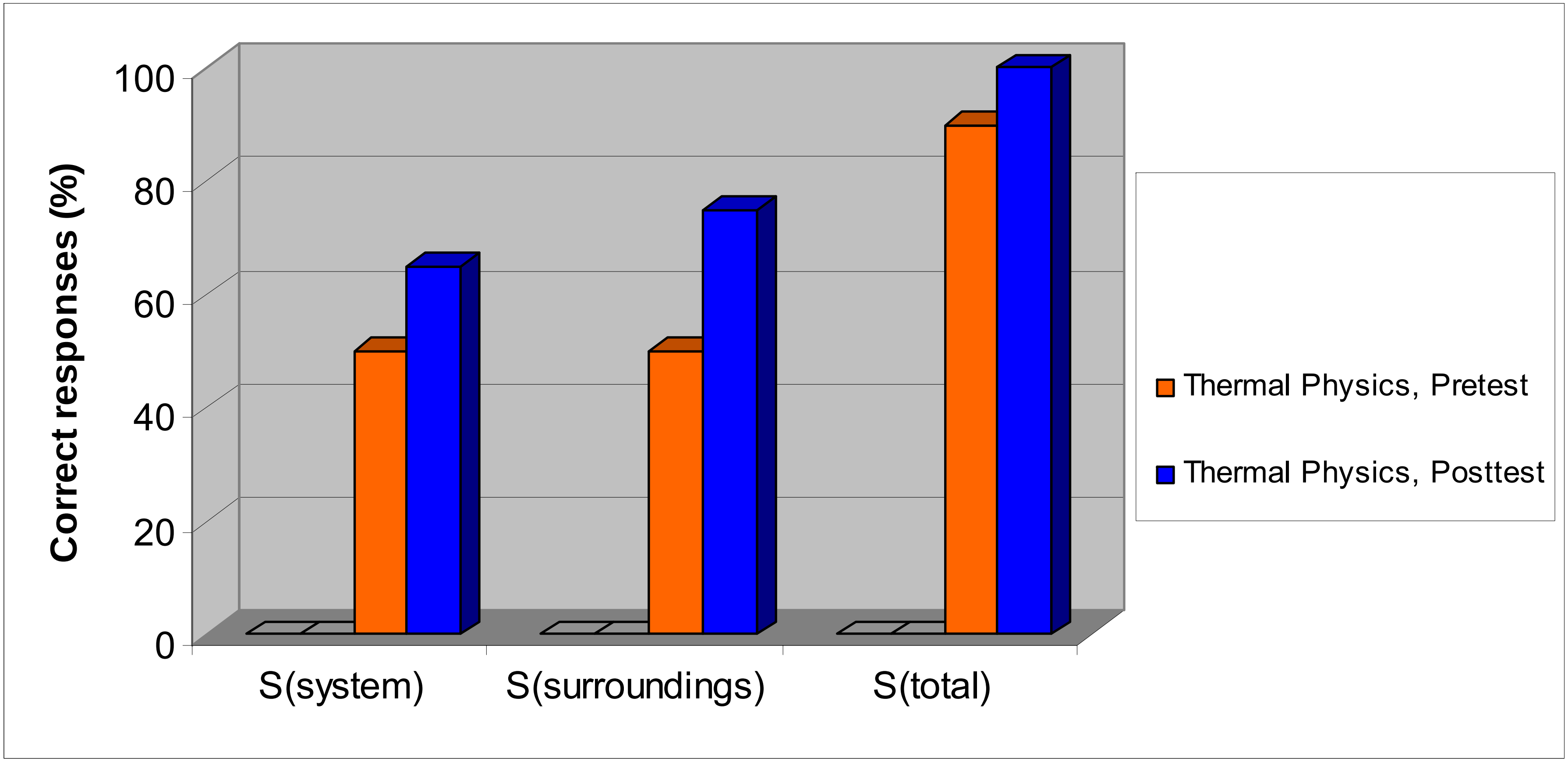
- Tendency to assume that "system entropy" must *always* increase

- Slow to accept the idea that entropy of system plus surroundings ***increases***

  - *Most students give incorrect answers to all three questions*

Responses to Spontaneous-Process Questions

Advanced Students



Thermal Physics Posttest: Interactive Engagement, no focused tutorial

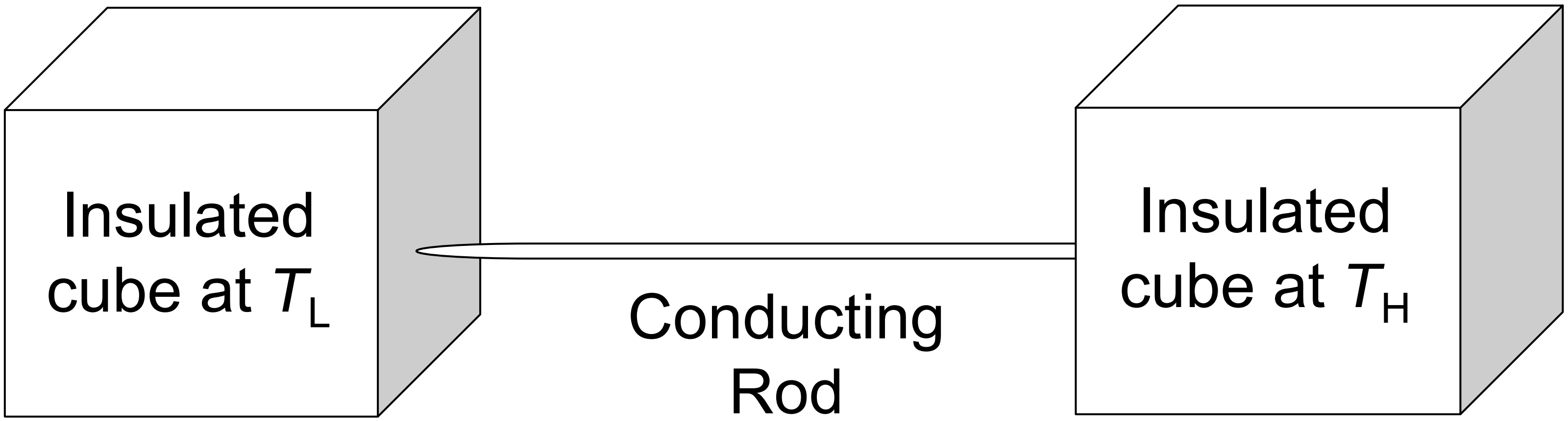
Thermal Physics Students' Thinking on Spontaneous Processes

- 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

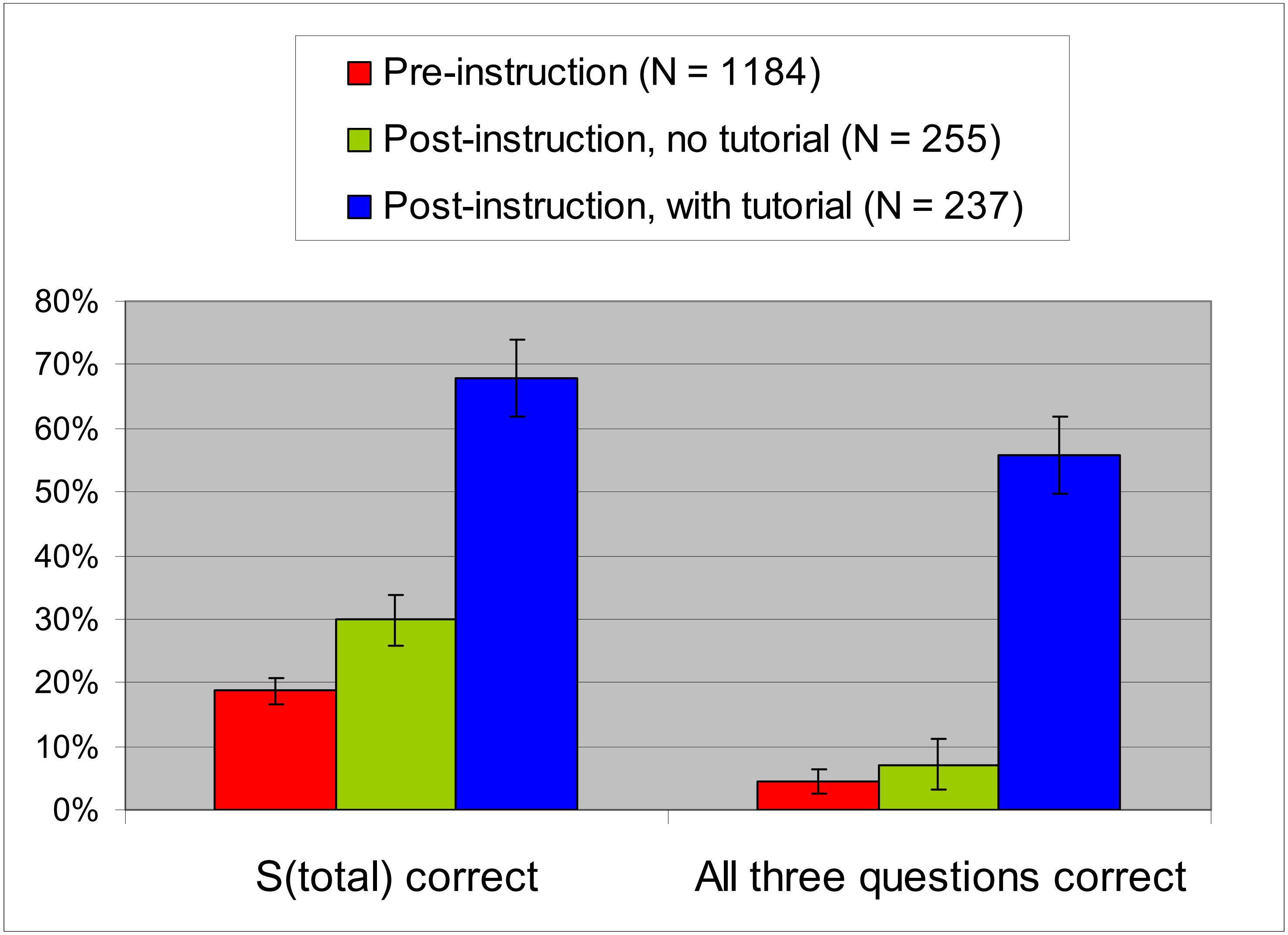
(draft by W. Christensen and DEM, undergoing class testing)

- Guide students to find that:

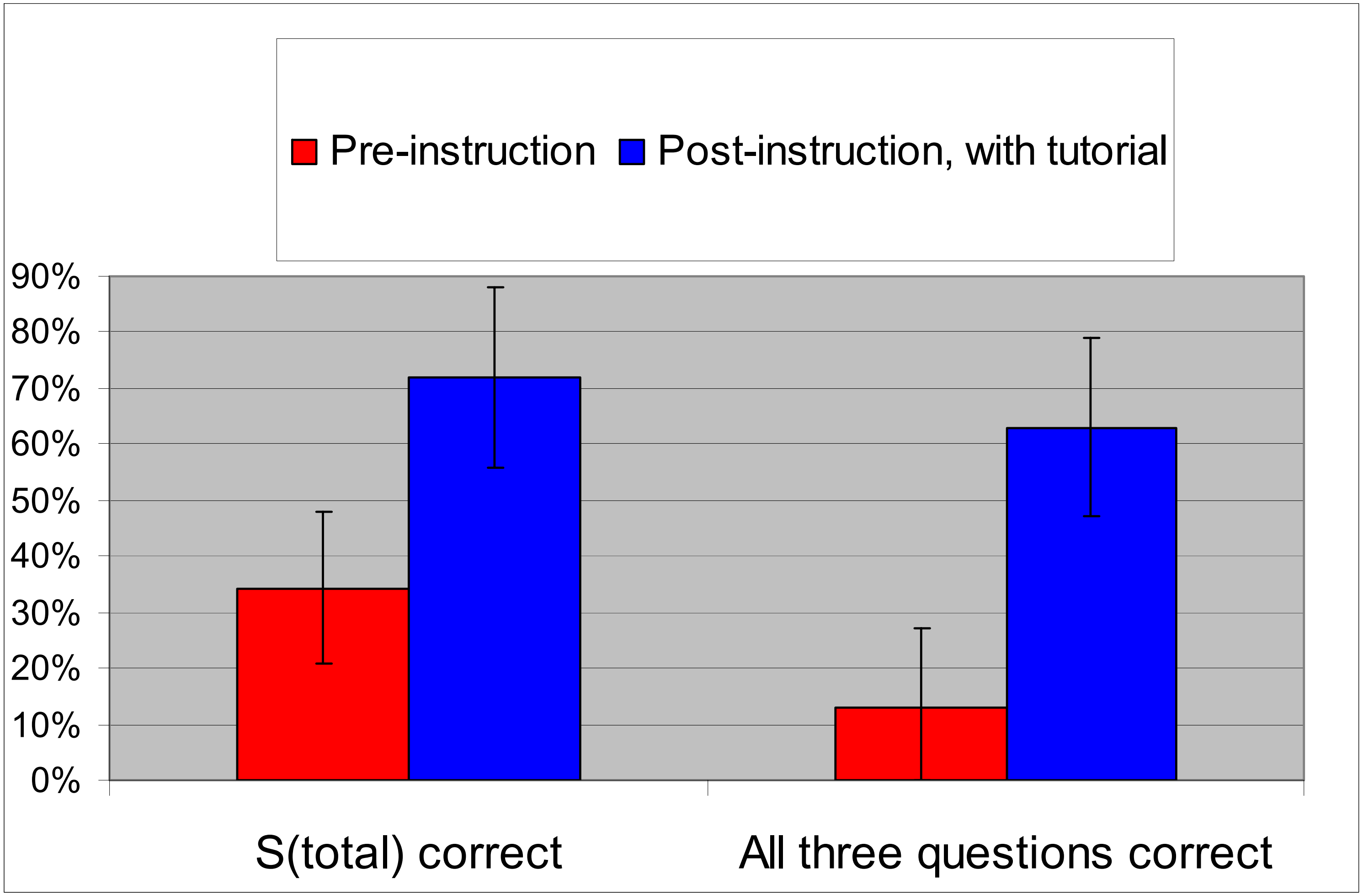
  and that definitions of "system" and "surroundings" are arbitrary

Preliminary results are promising…

Responses to Spontaneous-Process Questions
Introductory Students



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



Summary

- Difficulties with fundamental concepts found among introductory physics students persist for many students beginning upper-level thermal physics course.
- Intensive study incorporating active-learning methods yields only slow progress for many students.
- Large variations in performance among different students persist throughout course.