Addressing Students' Reasoning Difficulties in Thermal Physics

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Collaborators

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

Students

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

Recent studies of university students in general physics courses showed substantial learning difficulties with fundamental concepts, including heat, work, cyclic processes, and the first and second laws of thermodynamics.*

M. E. Loverude, C. H. Kautz, and P. R. L. Heron,* Am. J. Phys. ***70, 137 (2002);*

D. E. Meltzer, Am. J. Phys. ***72**, 1432 (2004);*

M. Cochran and P. R. L. Heron, Am. J. Phys. *(in press)*.

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

Methodological Issues

- Small class sizes imply large year-to-year fluctuations:
  - in student demographics
  - in student performance
- Broad range of preparation and abilities represented among students:
  - very hard to generalize results across sub-groups

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

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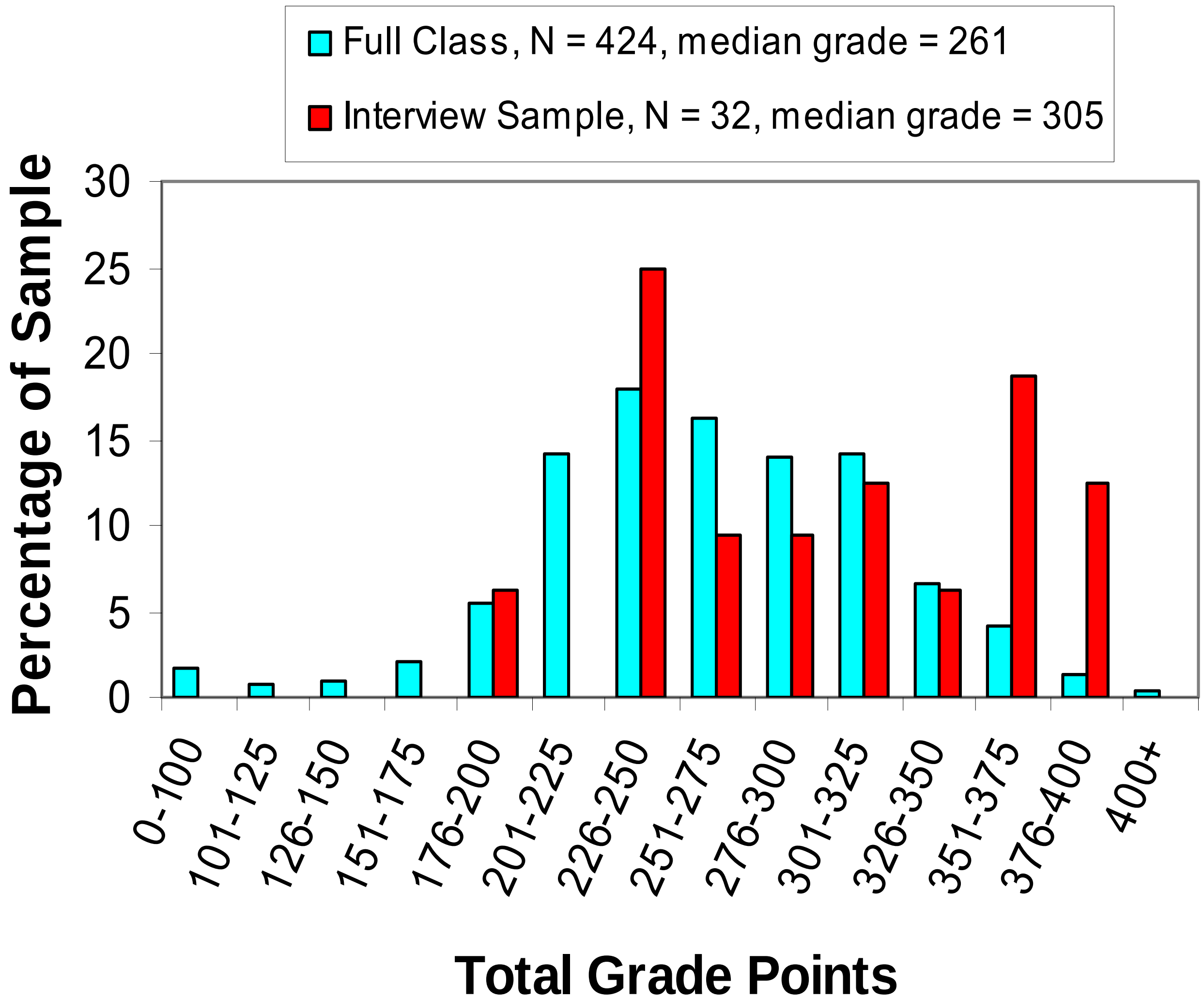
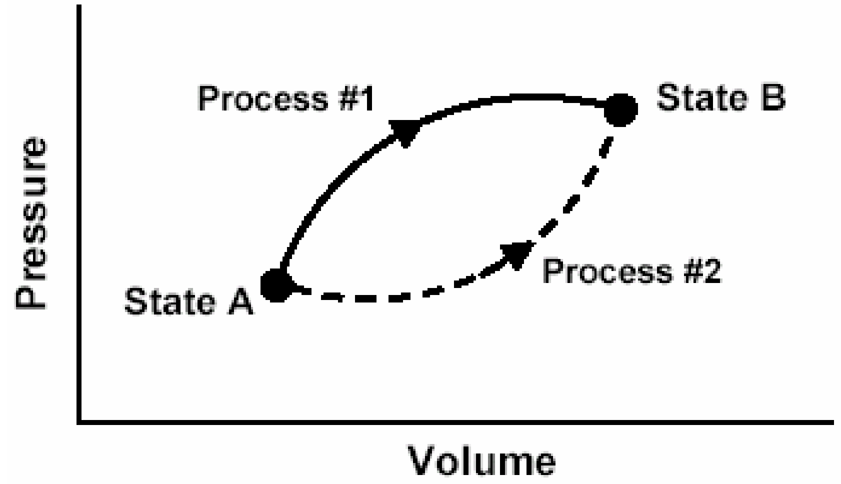
Grade Distributions: Interview Sample vs. Full Class



***Interview Sample*:**

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

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



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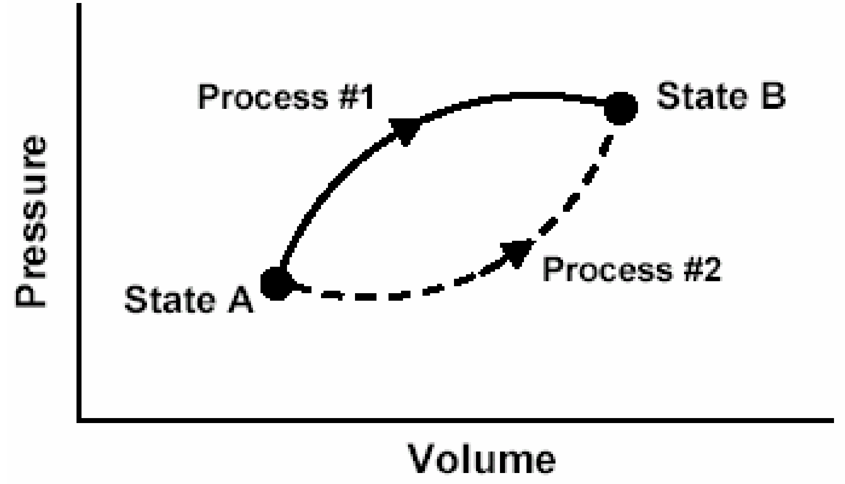

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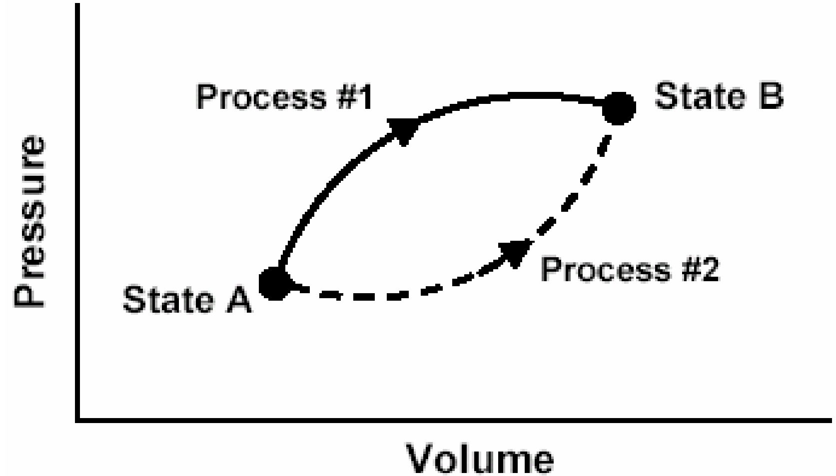

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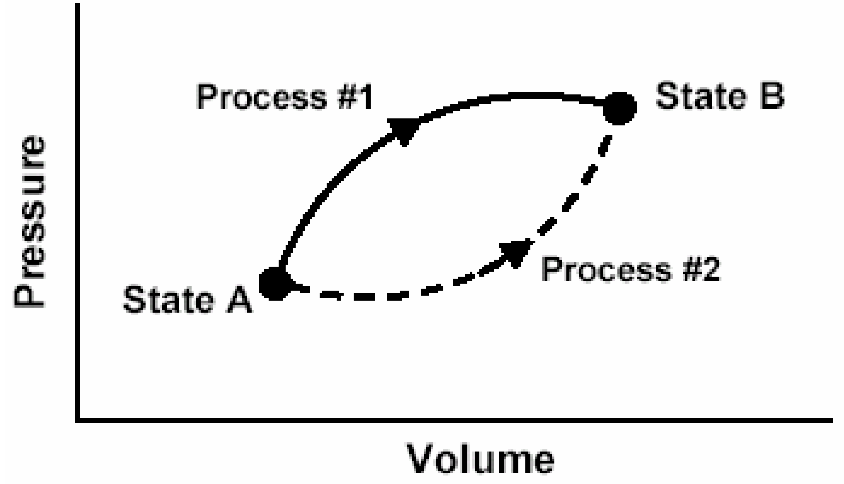

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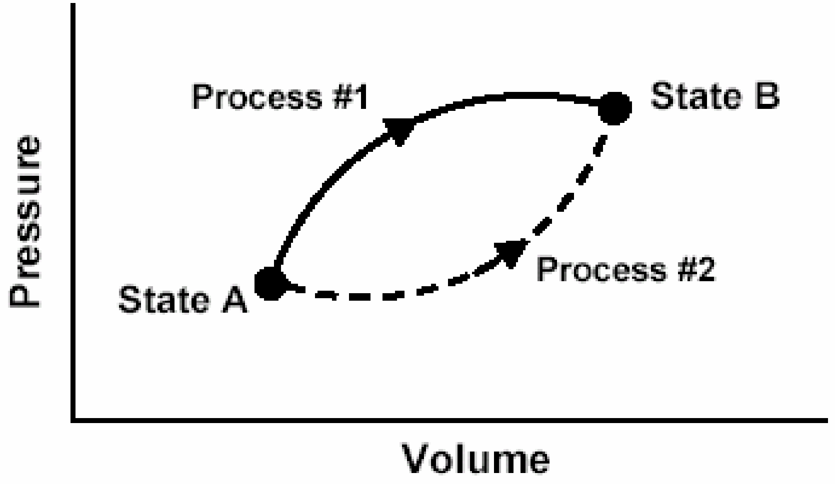

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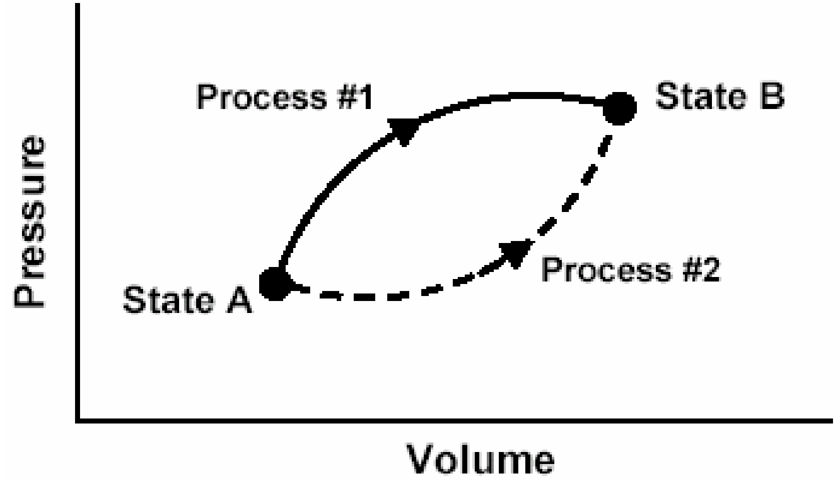

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Responses to Diagnostic Question #1
(Work question)

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

Responses to Diagnostic Question #1
(Work question)

$W_1 = W_2$			

Responses to Diagnostic Question #1
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	1999-2001 Introductory Physics (Post-test) Written Sample (N=653)		
$W_1 = W_2$	30%		

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

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	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
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$W_1 = W_2$	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 $W_1 = W_2$

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

Confusion with mechanical work done by conservative forces?

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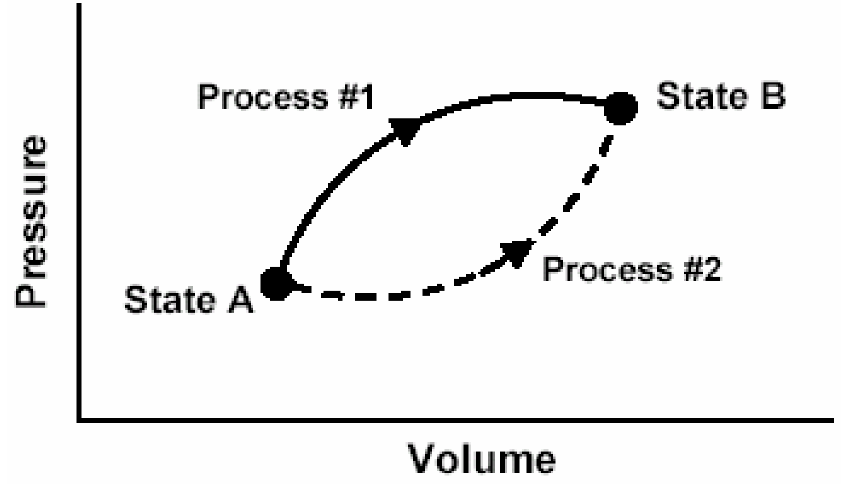

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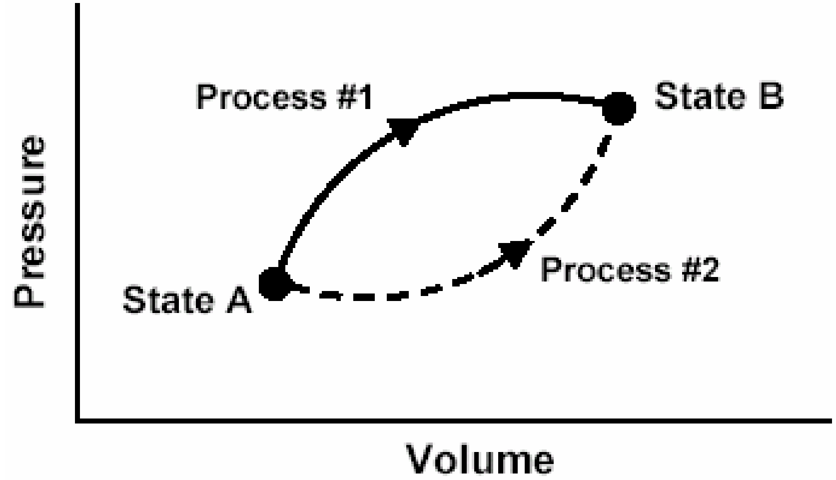

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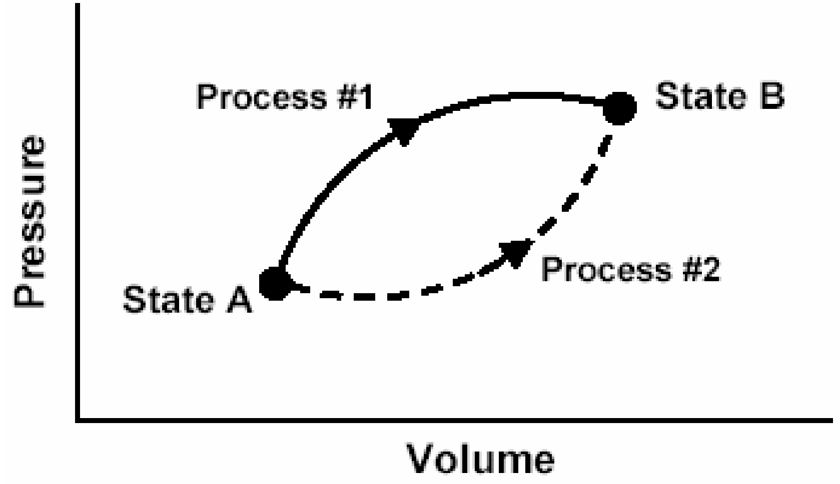
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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



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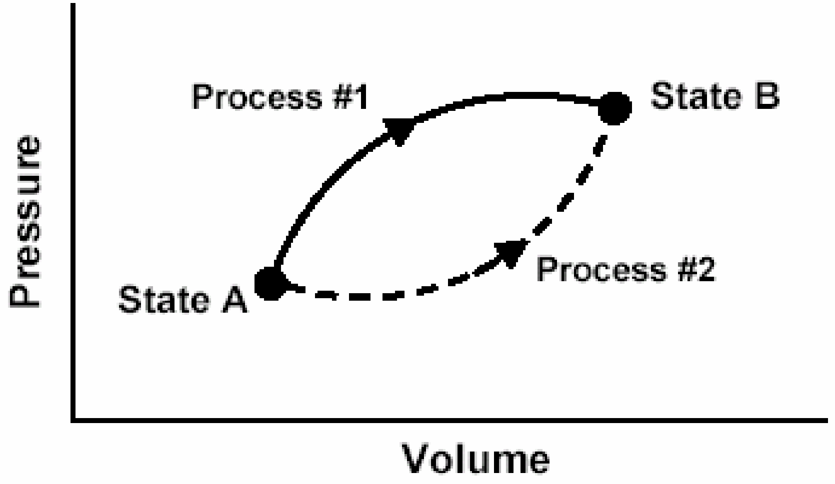
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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



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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)

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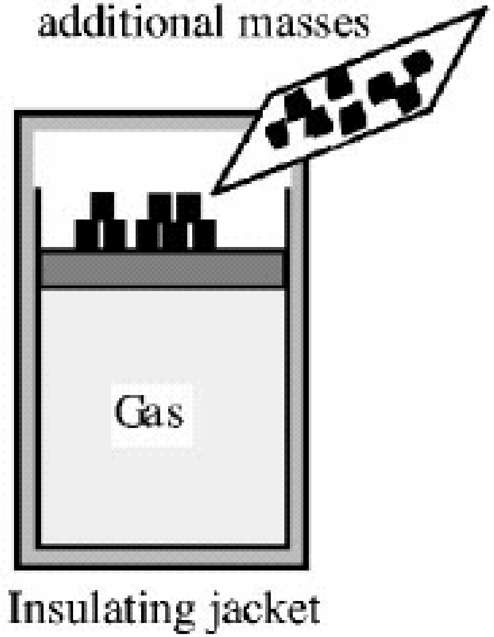
Performance of upper-level students significantly better than introductory students in *written* sample

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

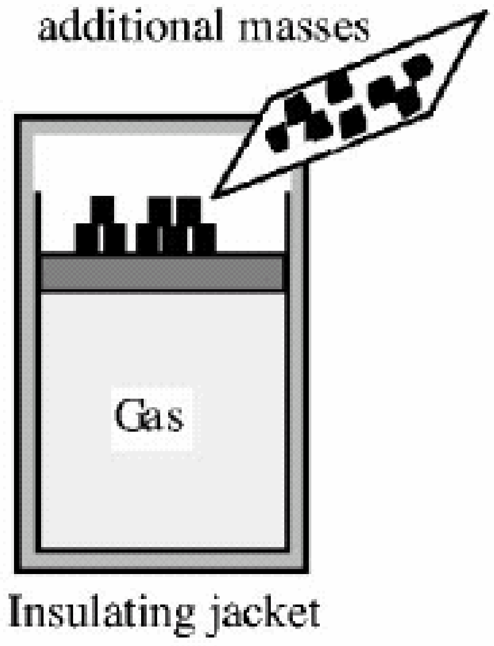


An ideal gas is contained in a cylinder with a tightly fitting piston. Several small masses are on the piston. (See diagram above.)

(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):

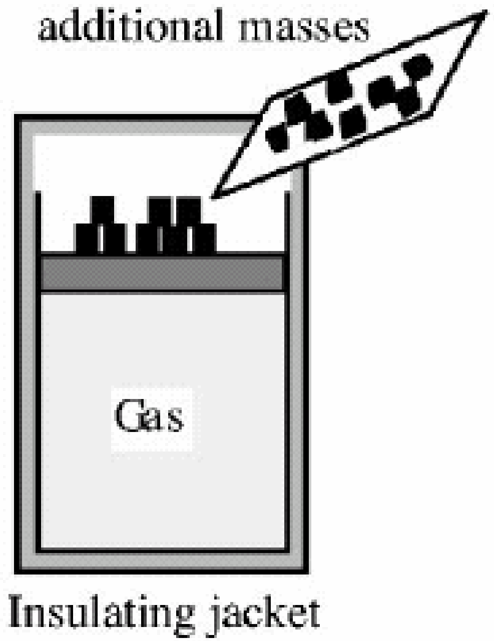
"*Work is done on the gas, but no heat transferred out, so T increases*."

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]

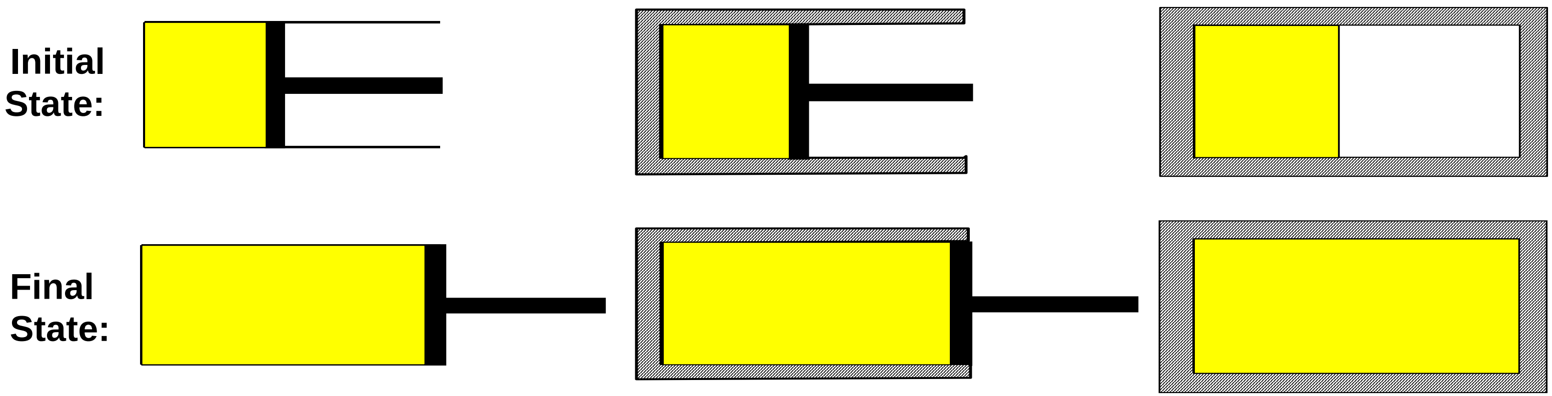
"*Temperature should stay the same due to insulating jacket* ." [2004]

"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.

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



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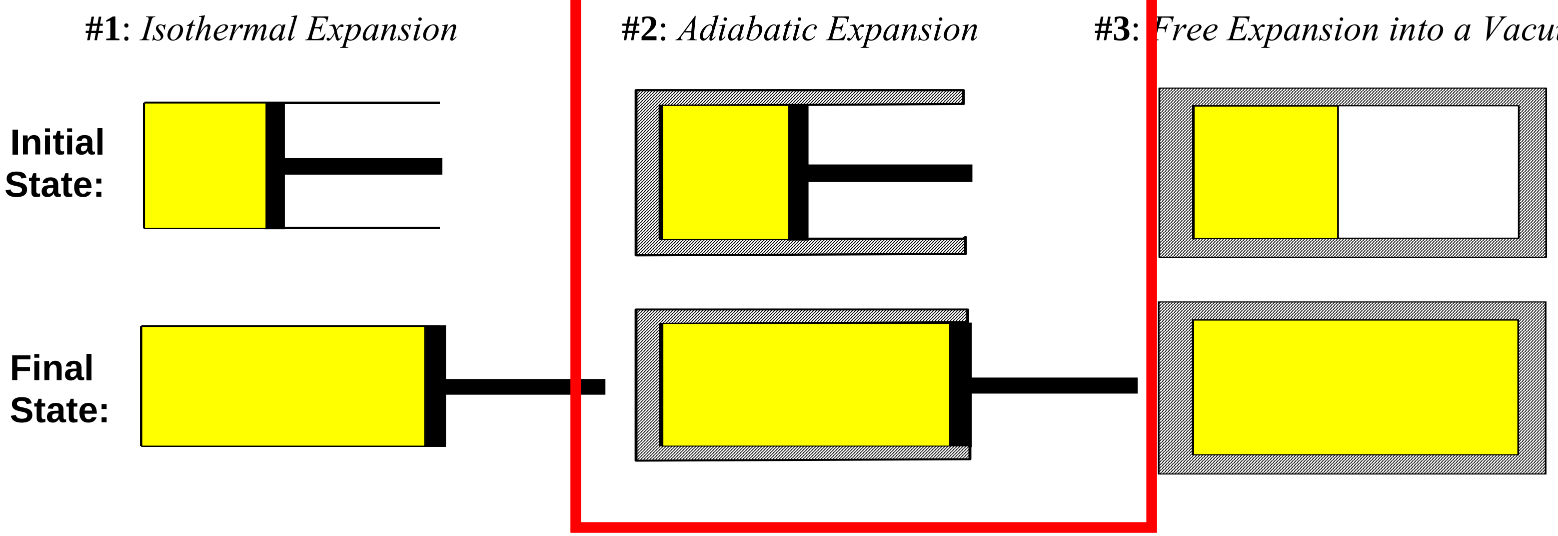

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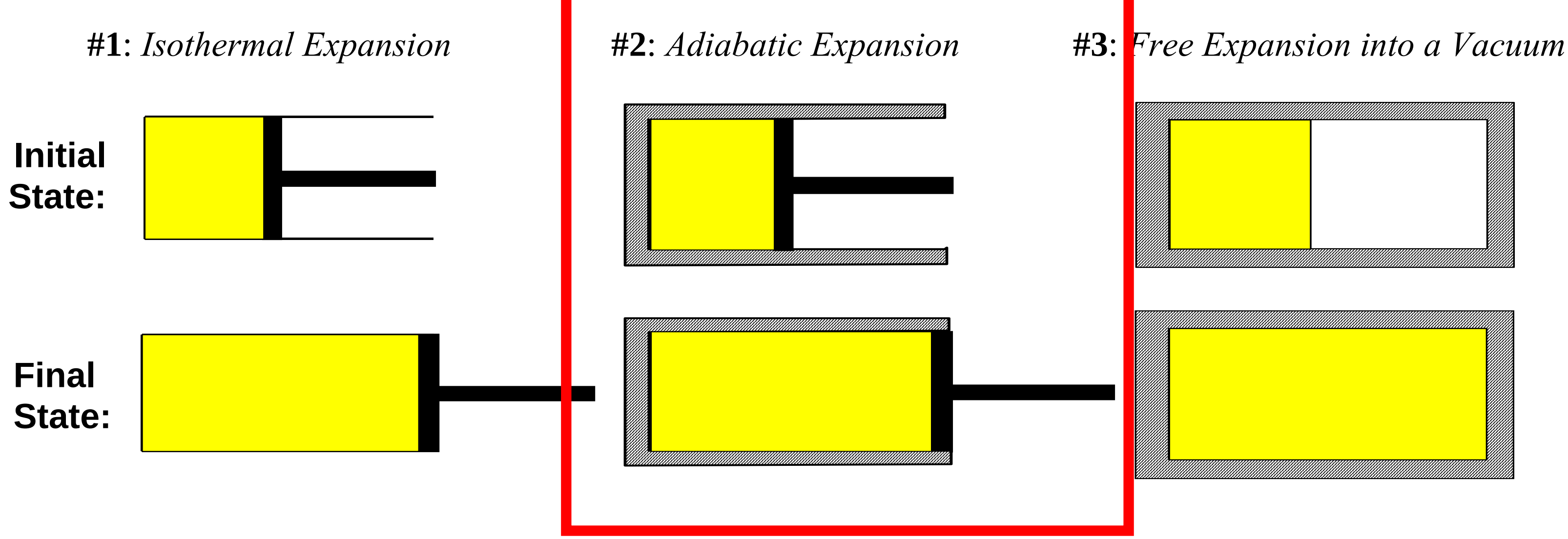

Is the change in internal energy *positive*, *negative*, or *zero*?

[University of Maine question]

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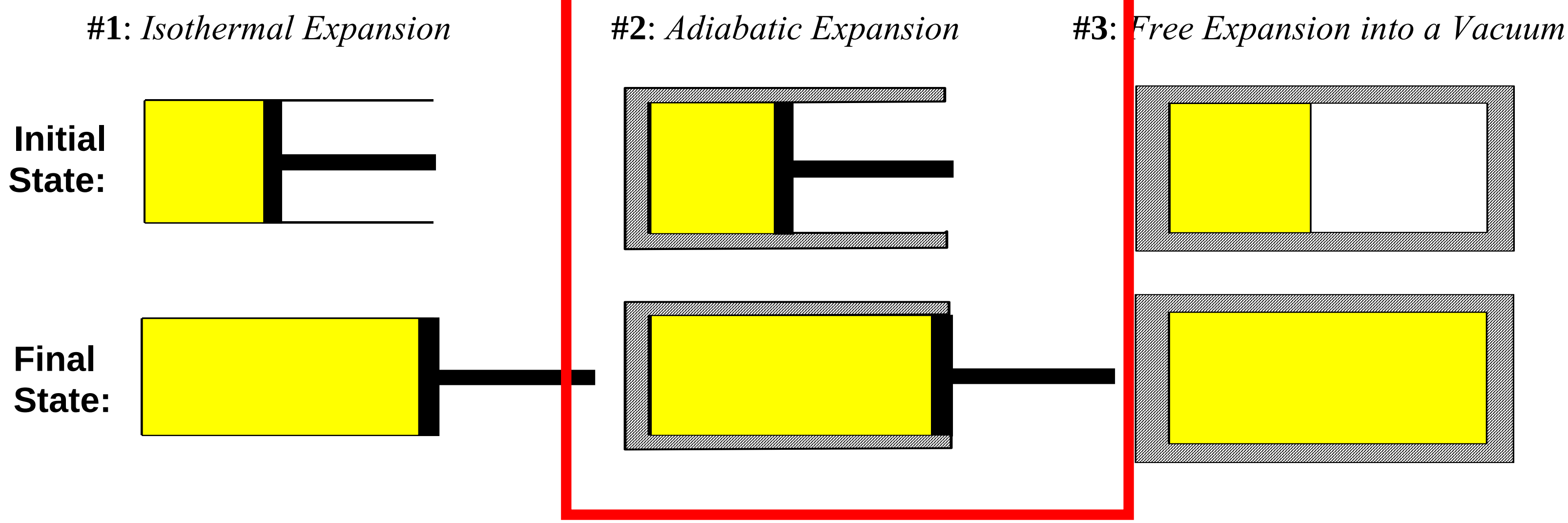


Is the change in internal energy *positive*, *negative*, or *zero*?

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	24%	0%
Insulated-piston problem incorrect on pretest	59%**	18%

*two students failed to show up for final
**several students used *W*-equation improperly

Cyclic Process Questions

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

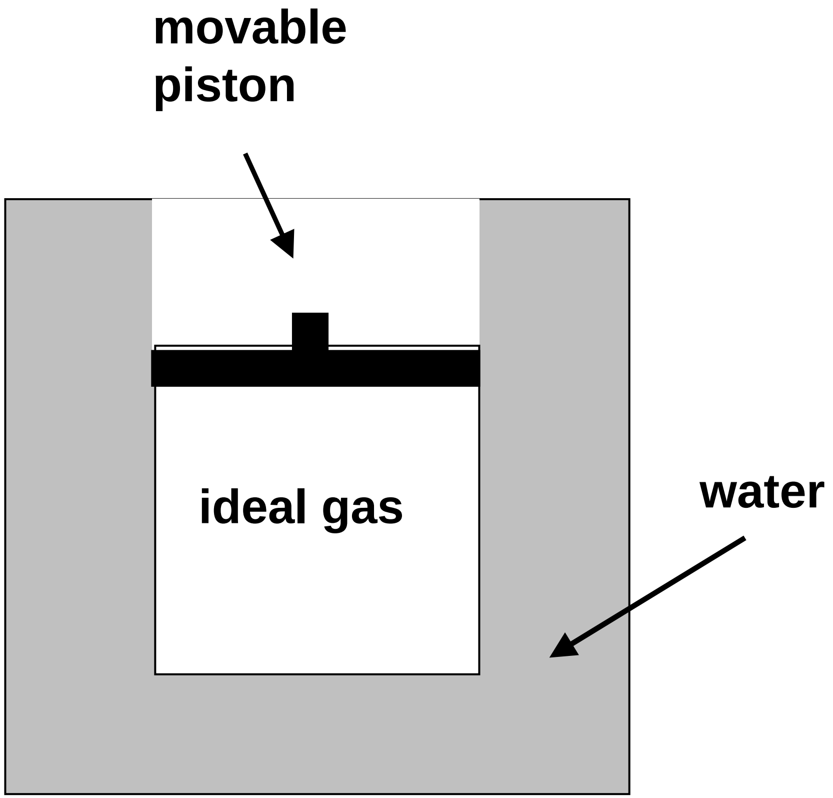
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

Cyclic Process Questions

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

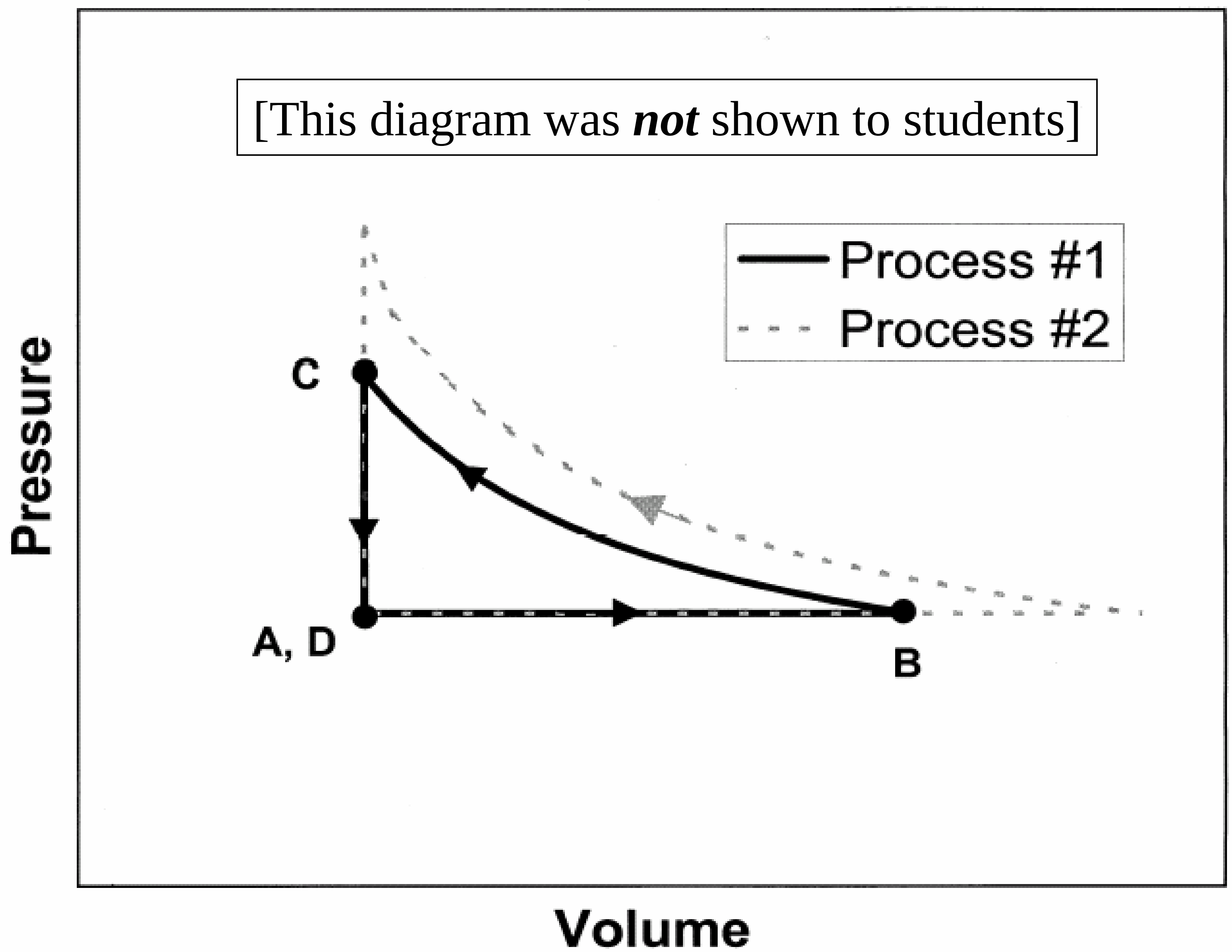
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

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

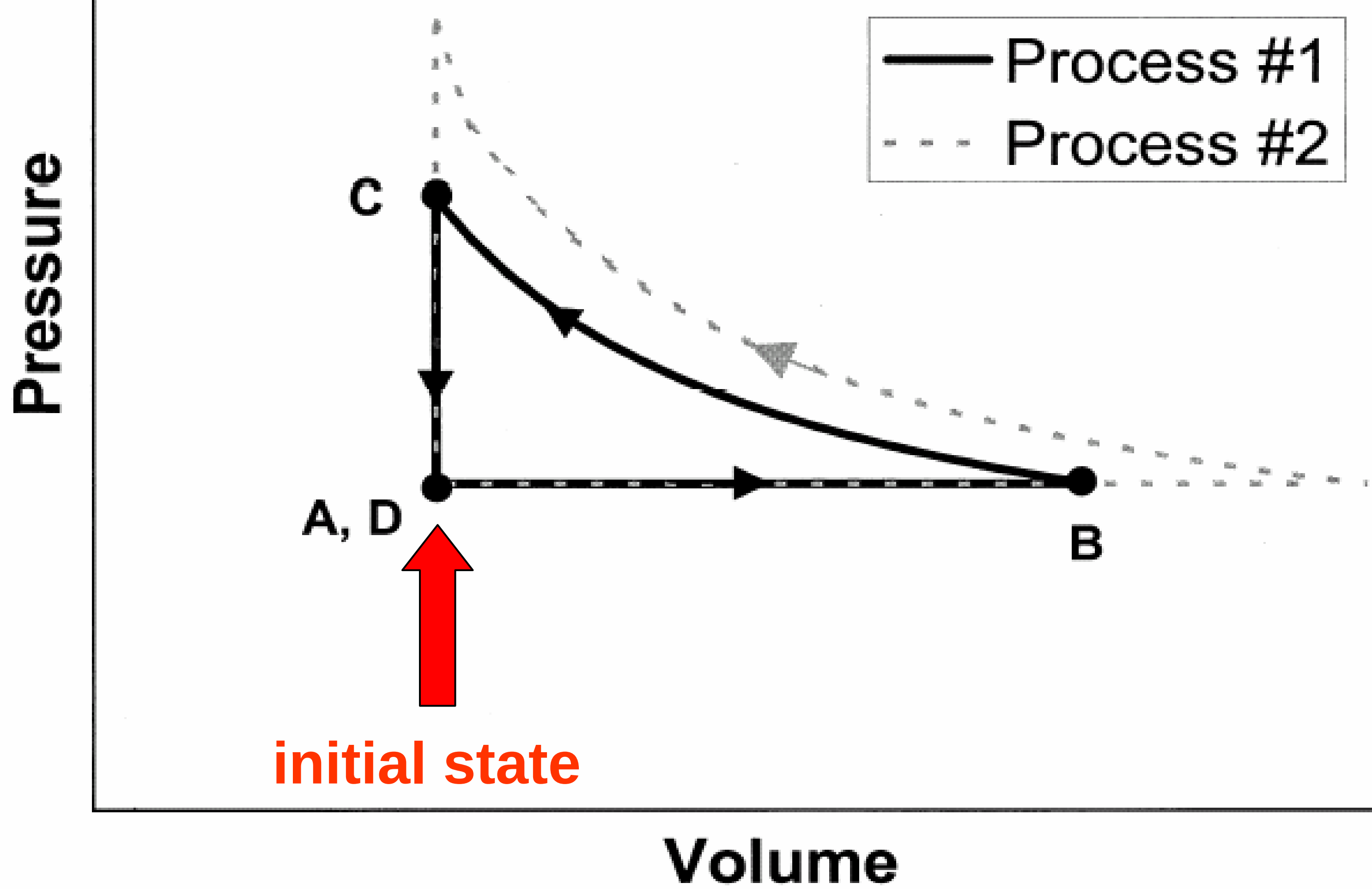


Time *A*

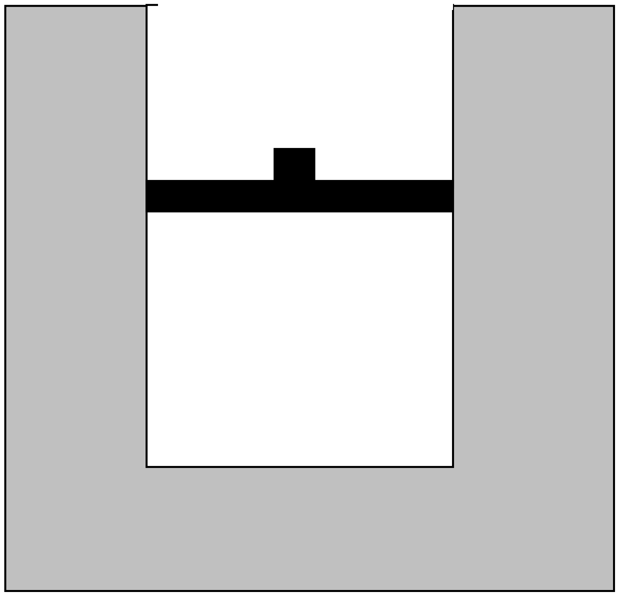
Entire system at room temperature.

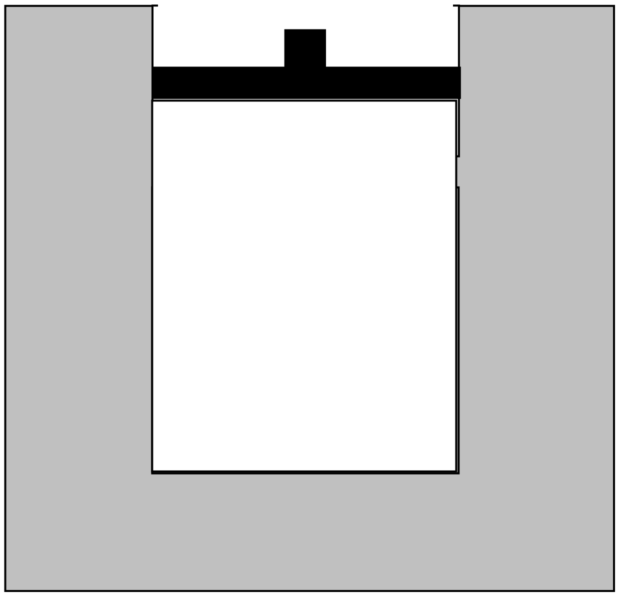

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

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

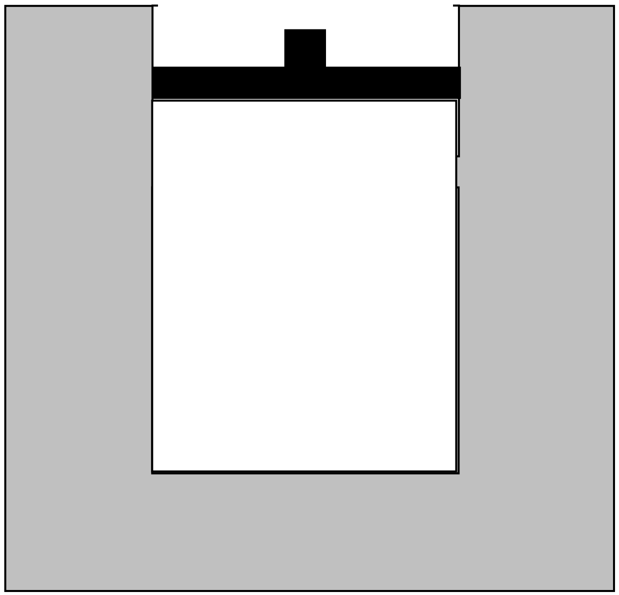


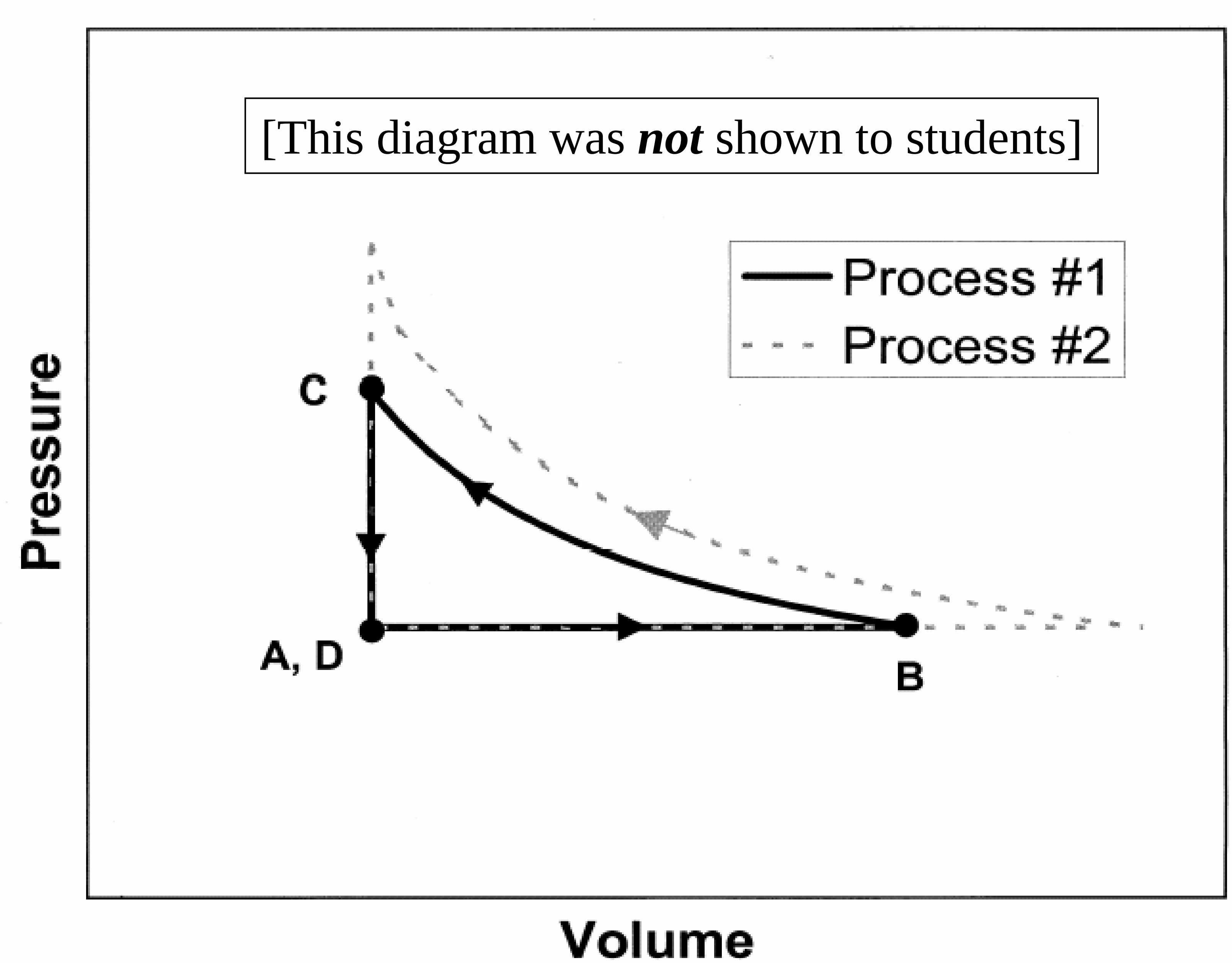
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.



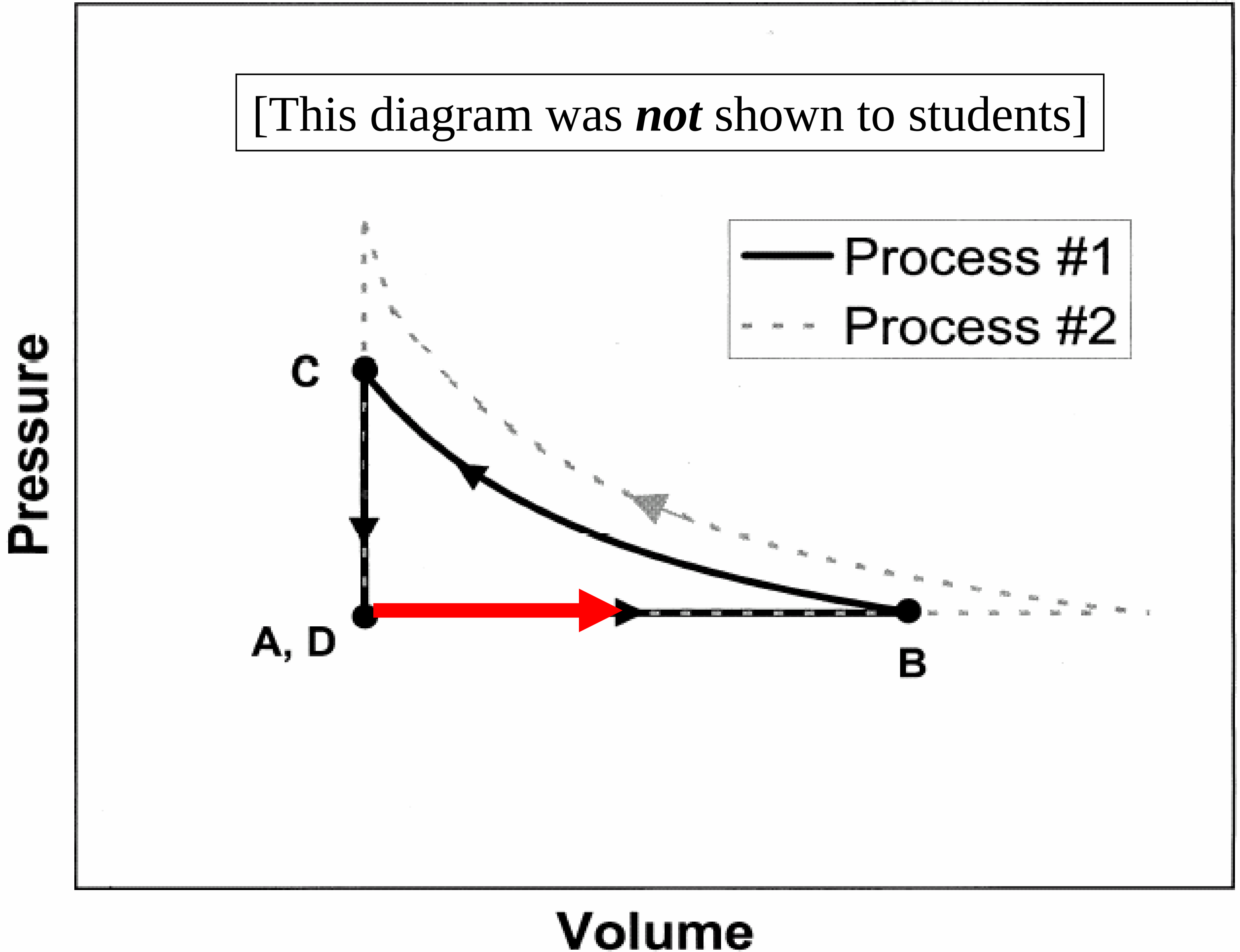


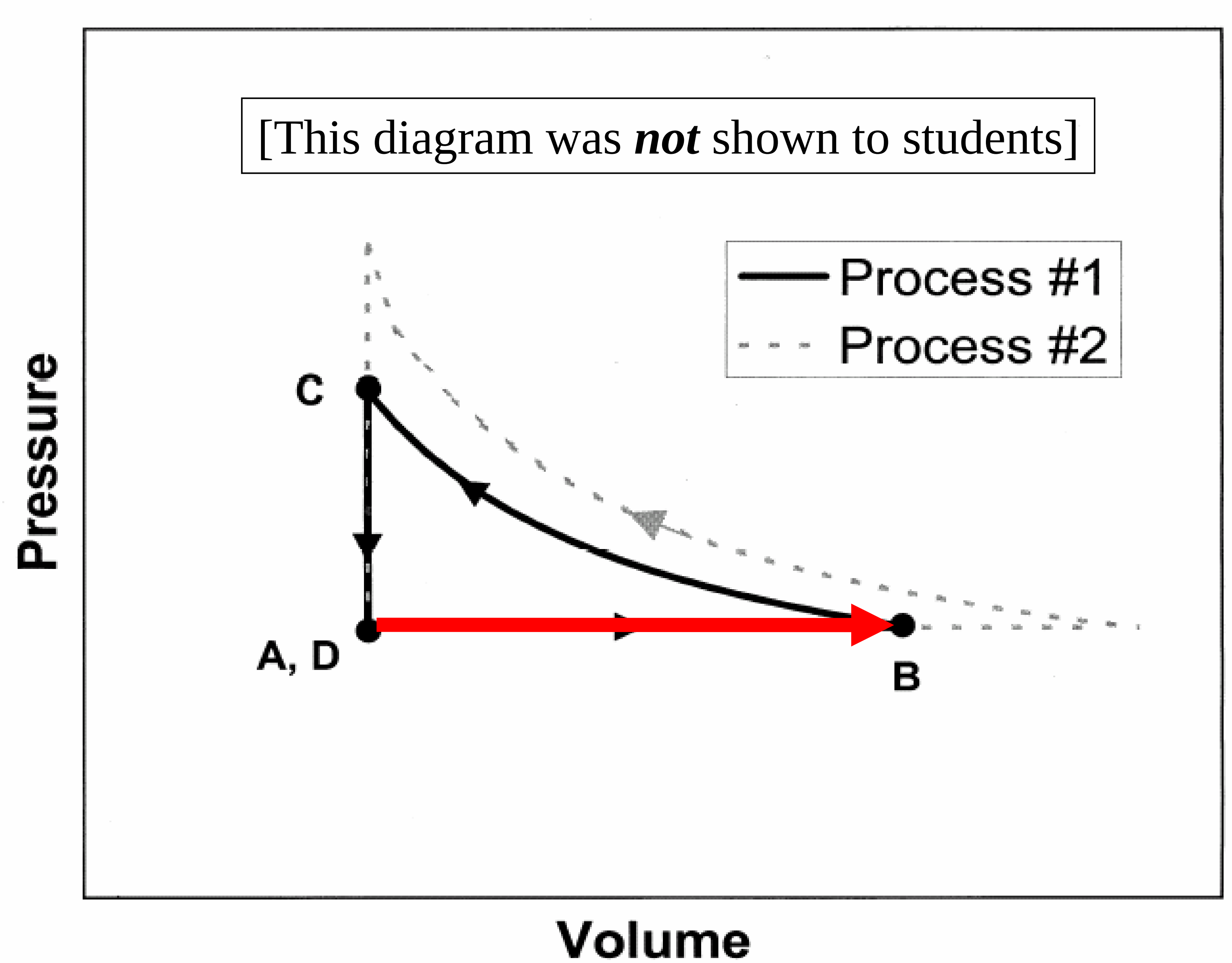
At time ***B*** the heating of the water stops, and the piston stops moving




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

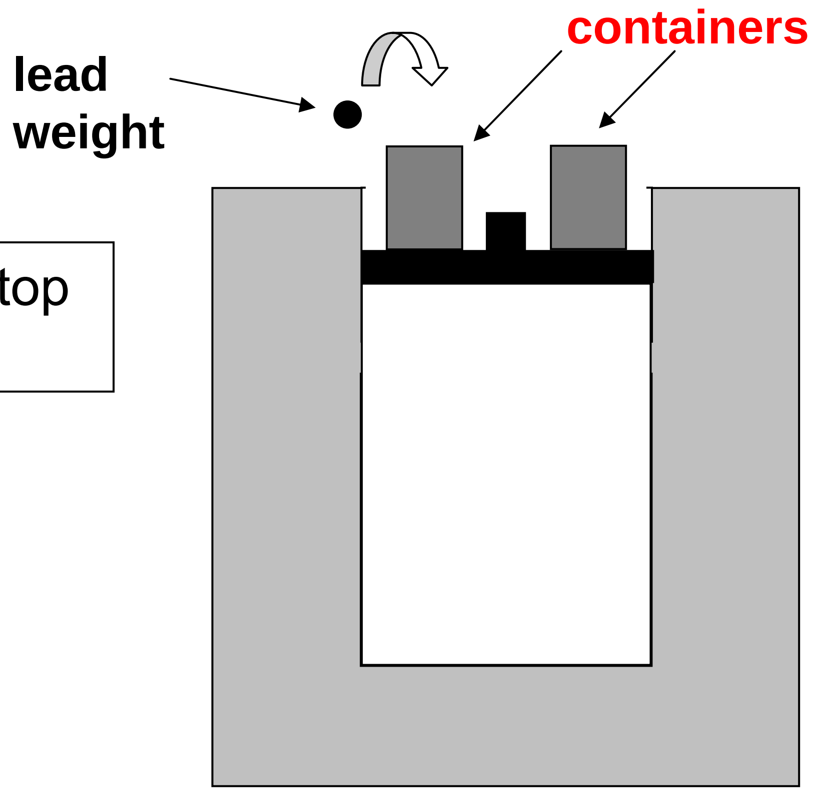
[This diagram was ***not*** shown to students]



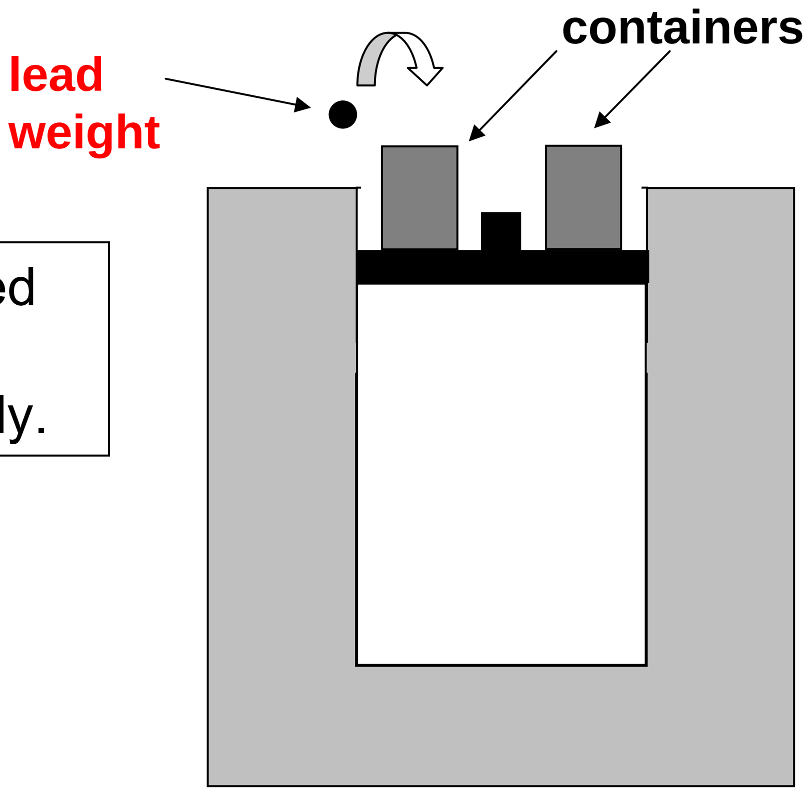


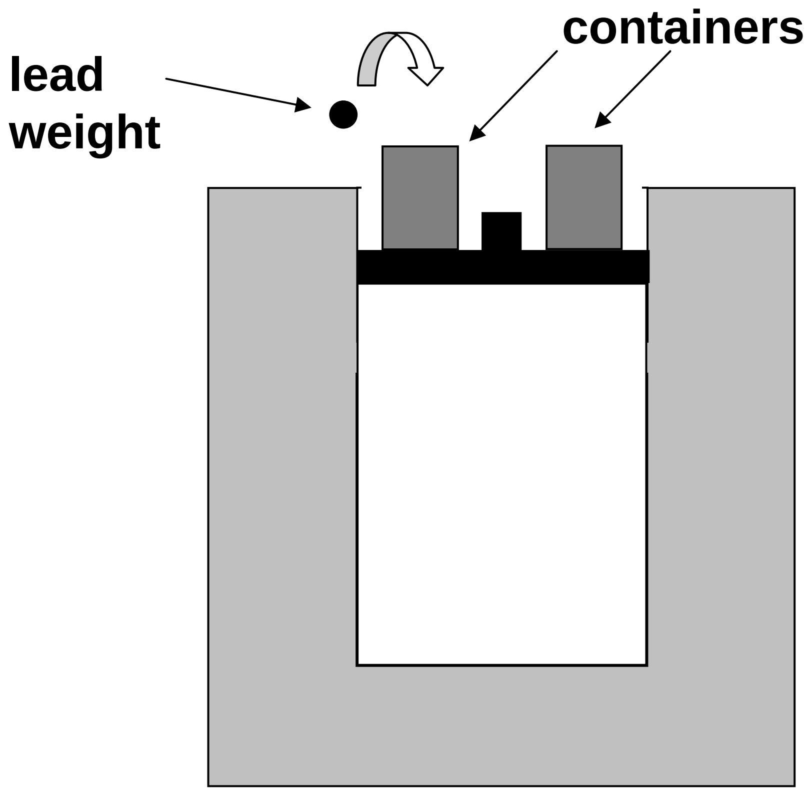
[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

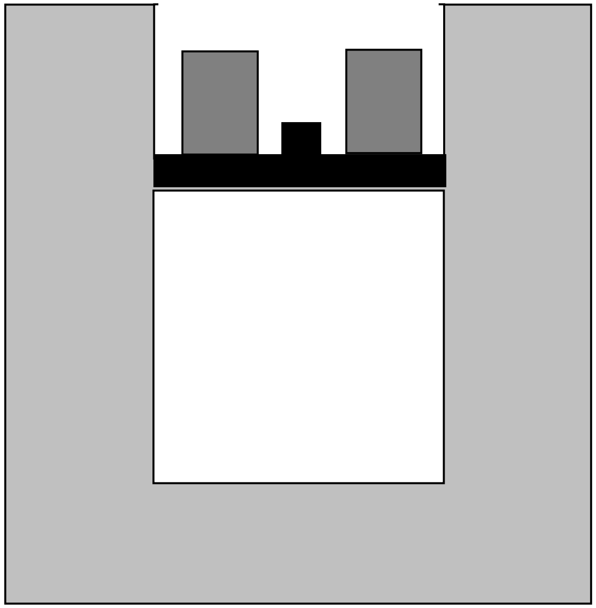
Now, empty containers are placed on top of the piston as shown.



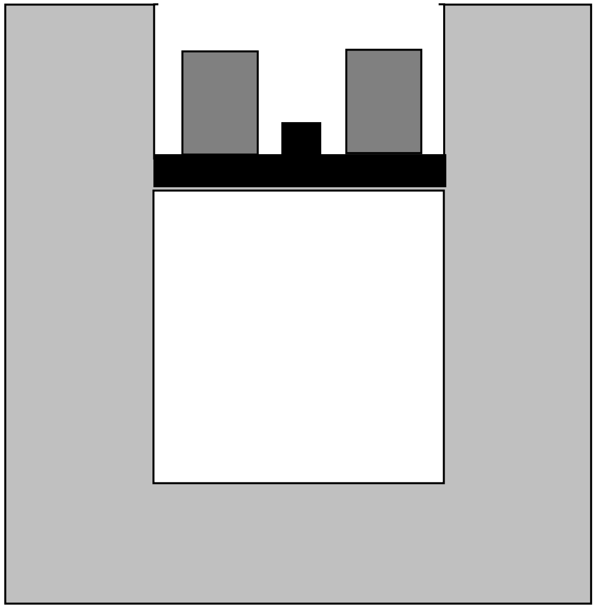
Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly.



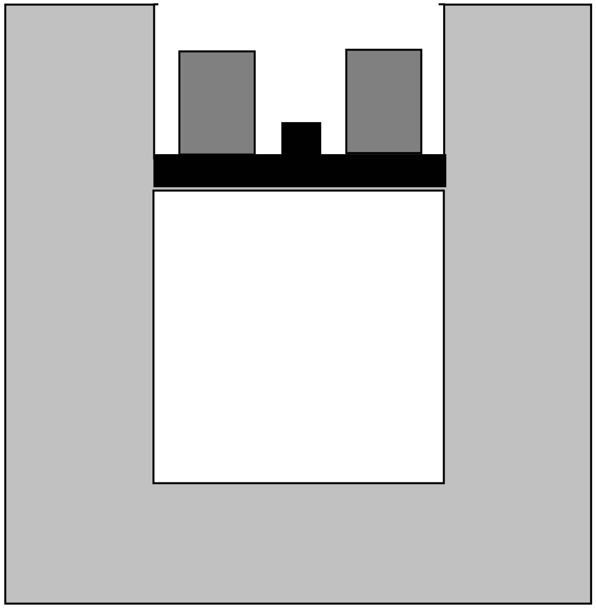

containers
lead
weight



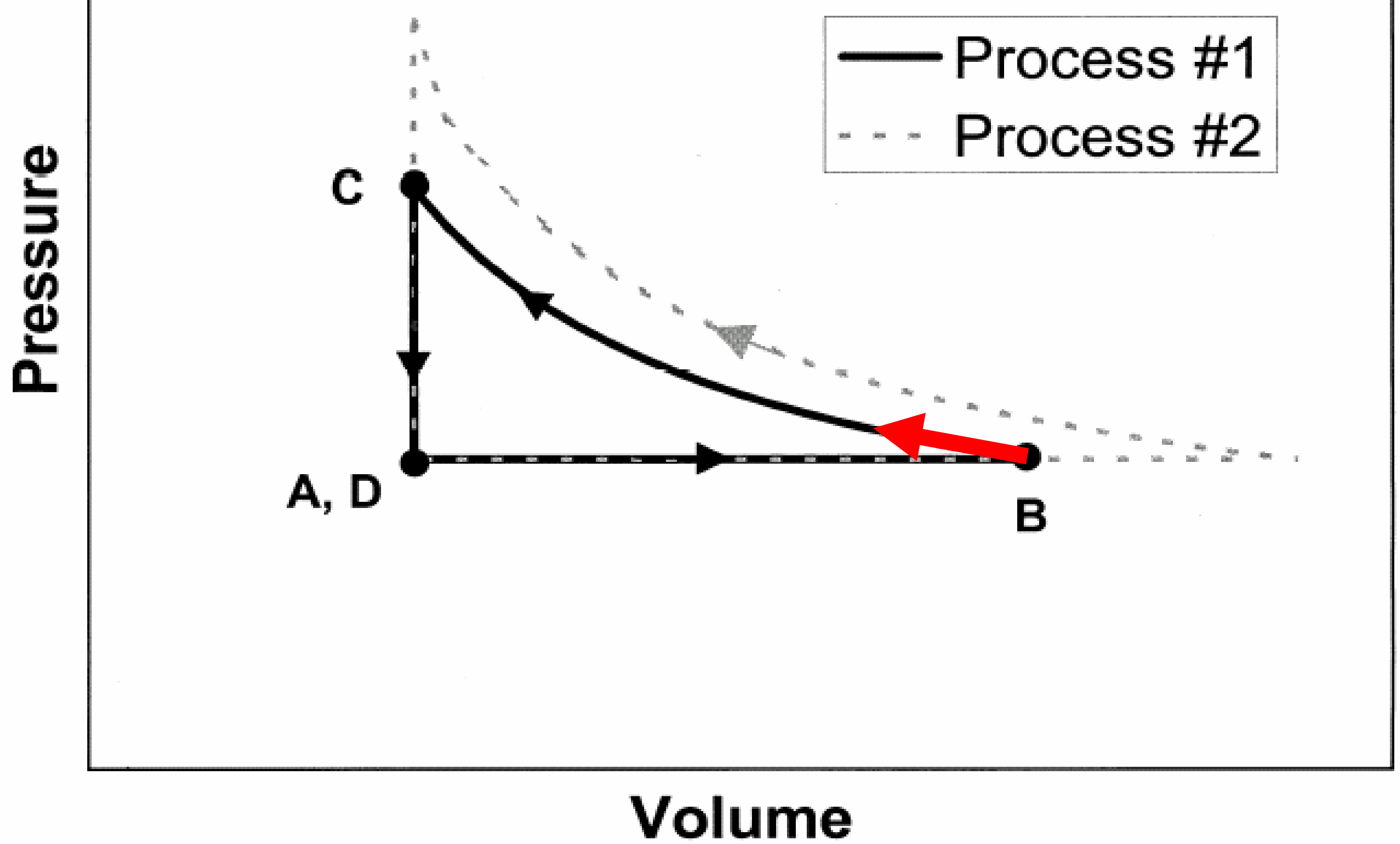
While this happens the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*.



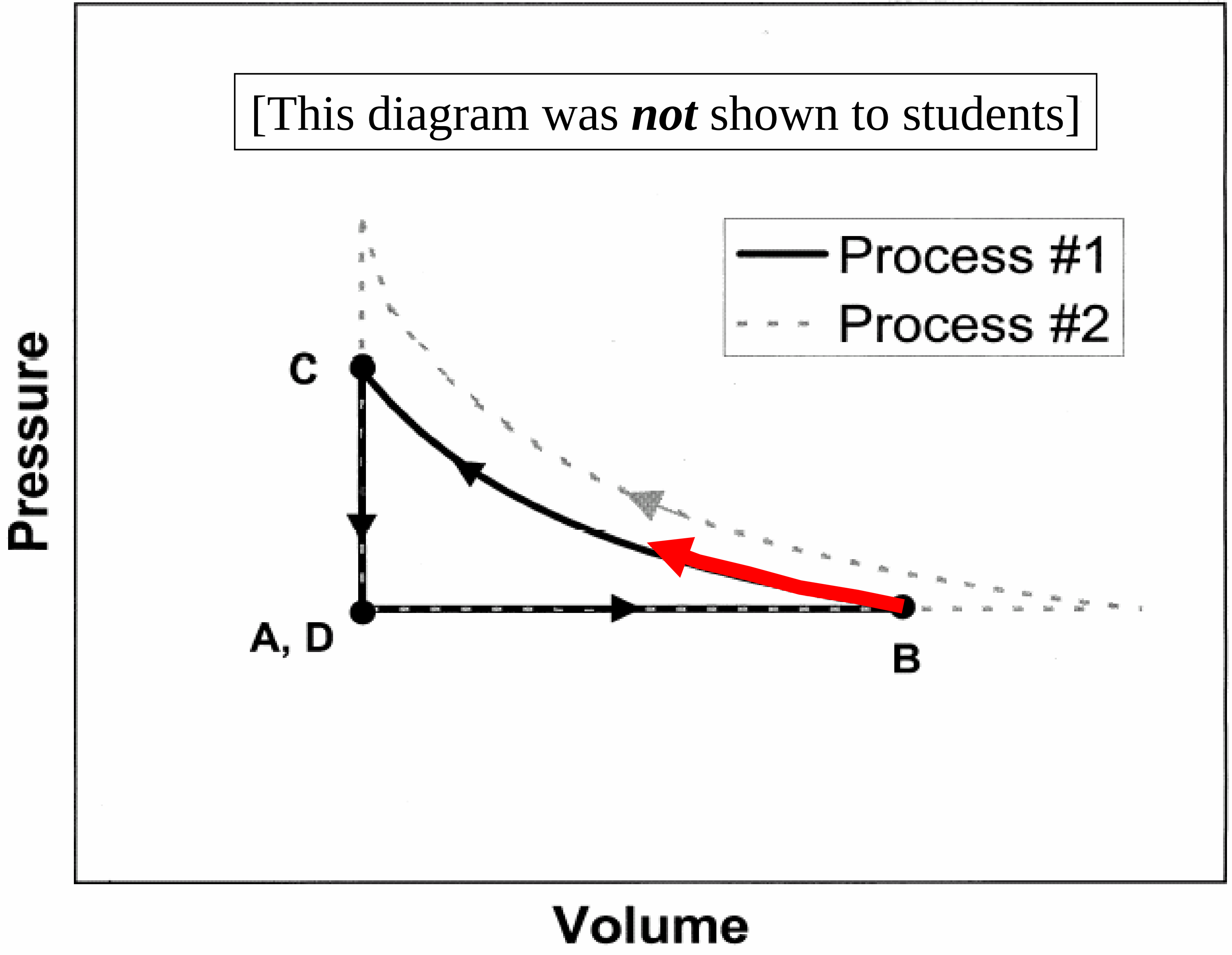
At time ***C*** we stop adding lead weights to the container and the piston stops moving. The piston is now at exactly the same position it was at time ***A*** .

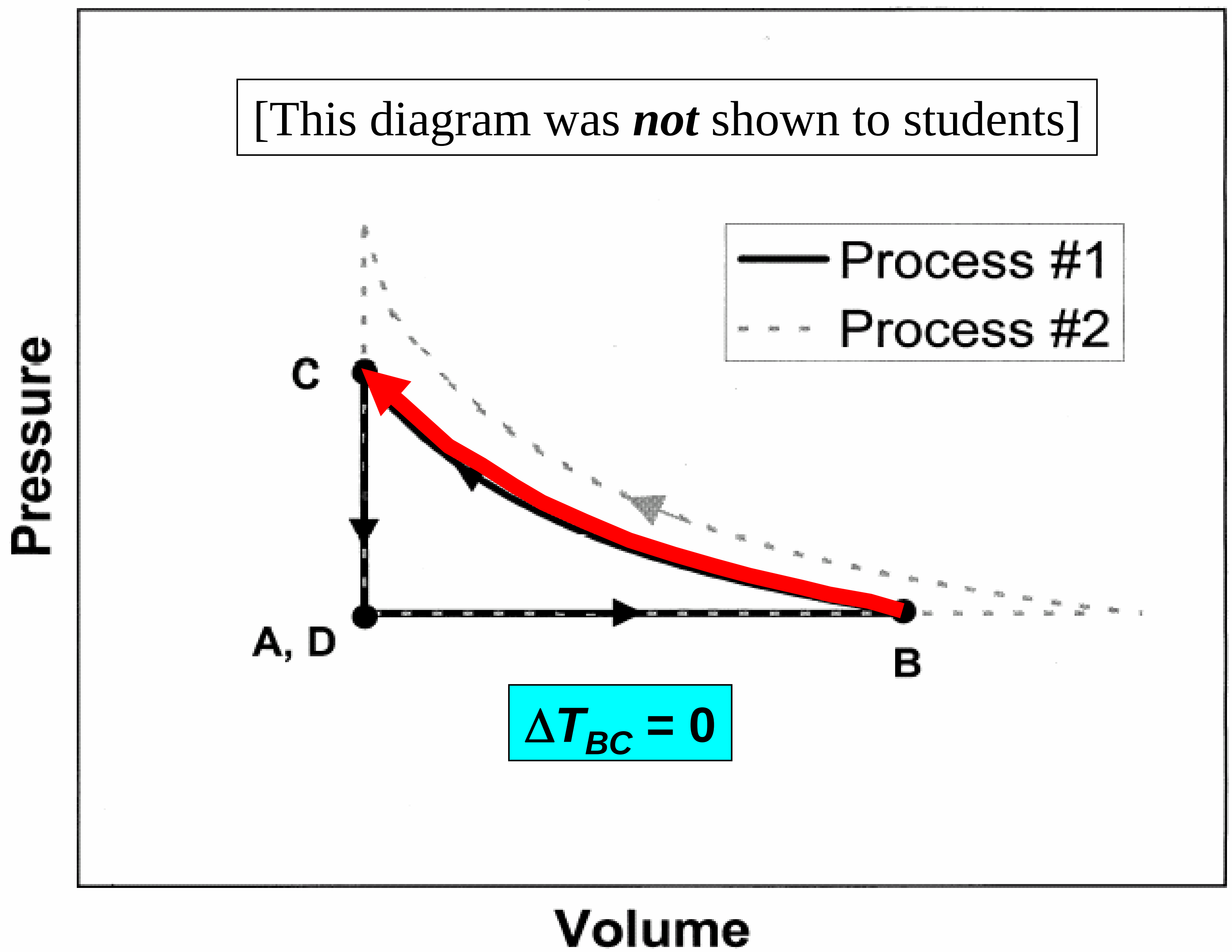


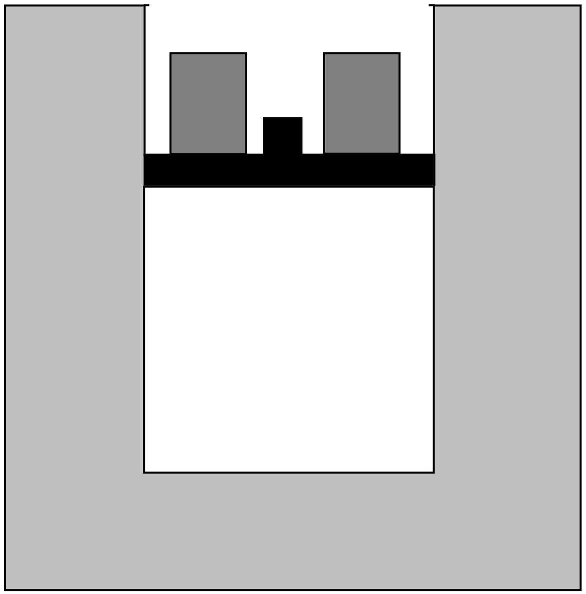
[This diagram was ***not*** shown to students]



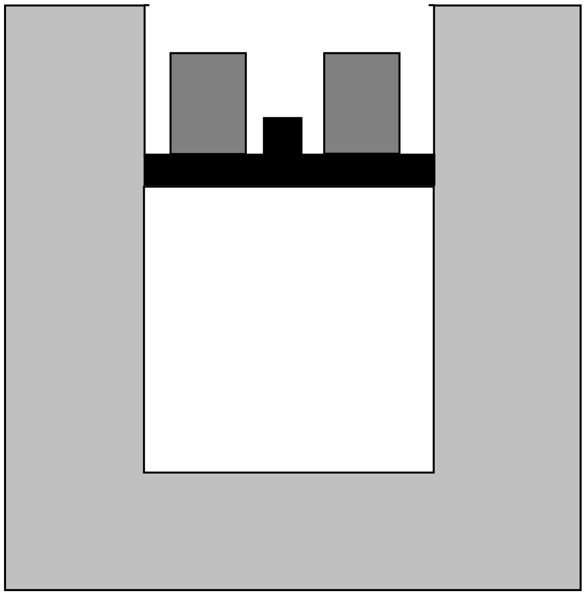
[This diagram was ***not*** shown to students]




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

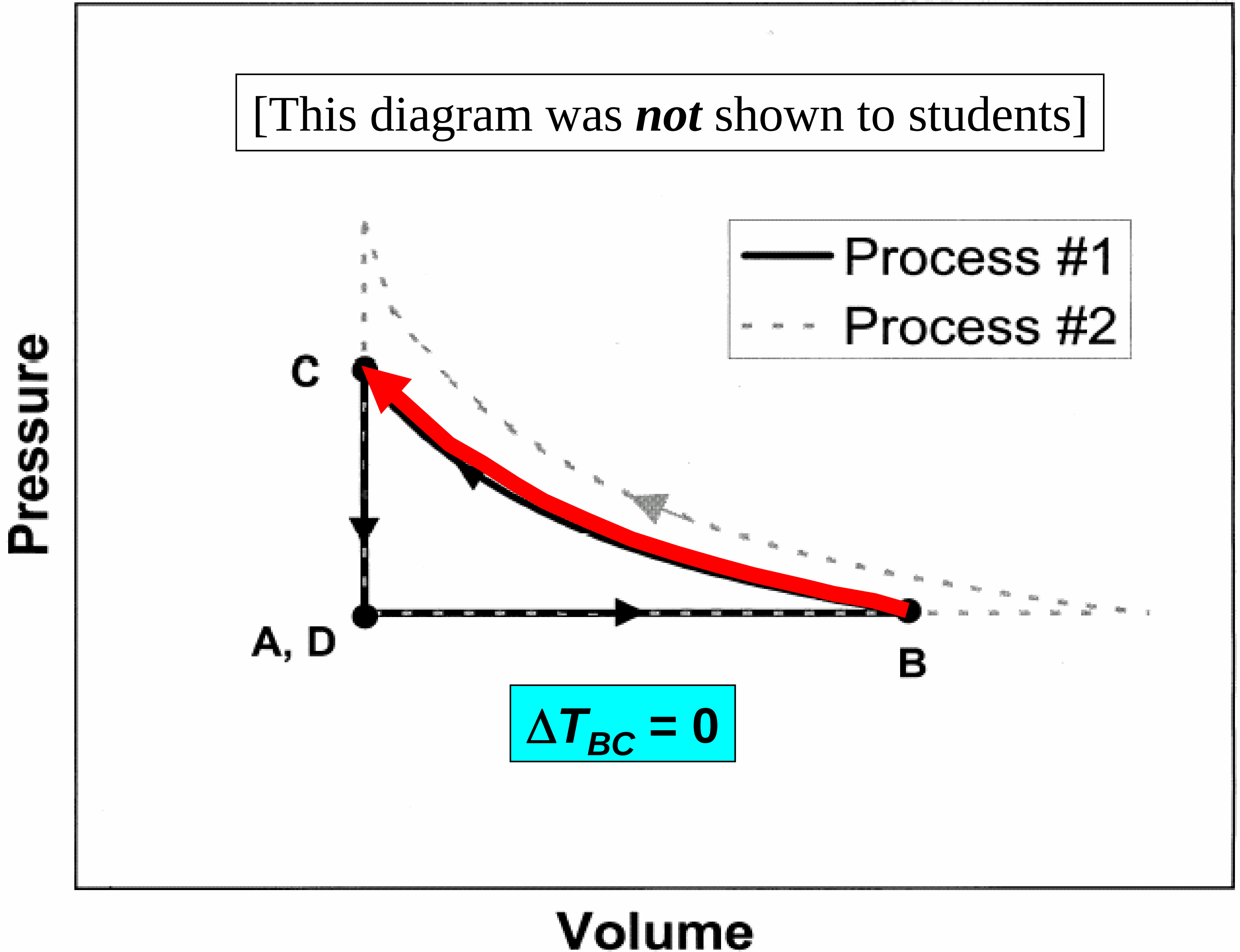


Question #4: During the process that occurs from time *B* to time *C*, is there *any* net energy flow between the gas and the water? If no, explain why not. If yes, is there a net flow of energy from gas to water, or from water to gas?



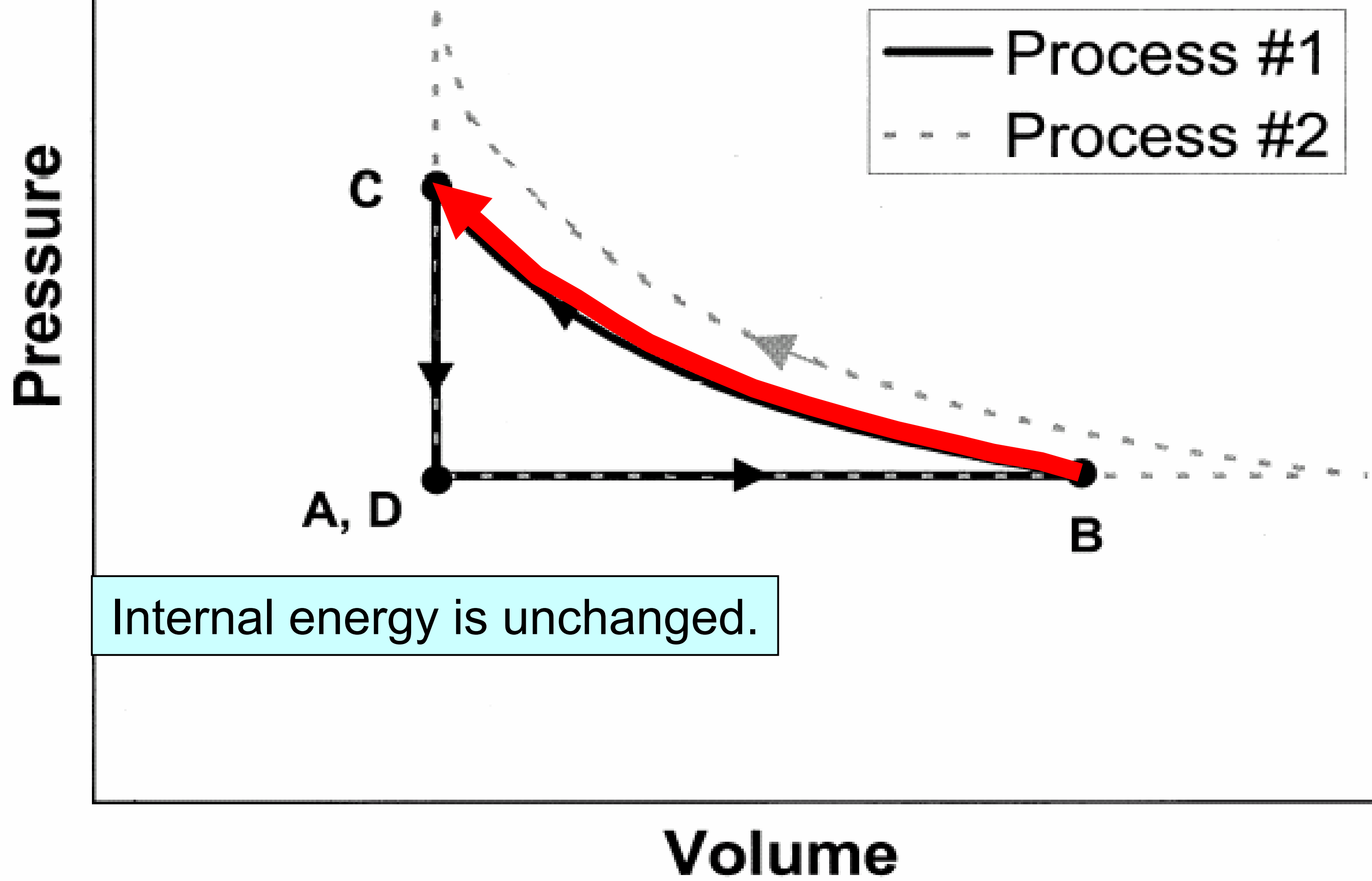
Question #4: During the process that occurs from time *B* to time *C*, is there *any* net energy flow between the gas and the water? If no, explain why not. If yes, is there a net flow of energy from gas to water, or from water to gas?

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

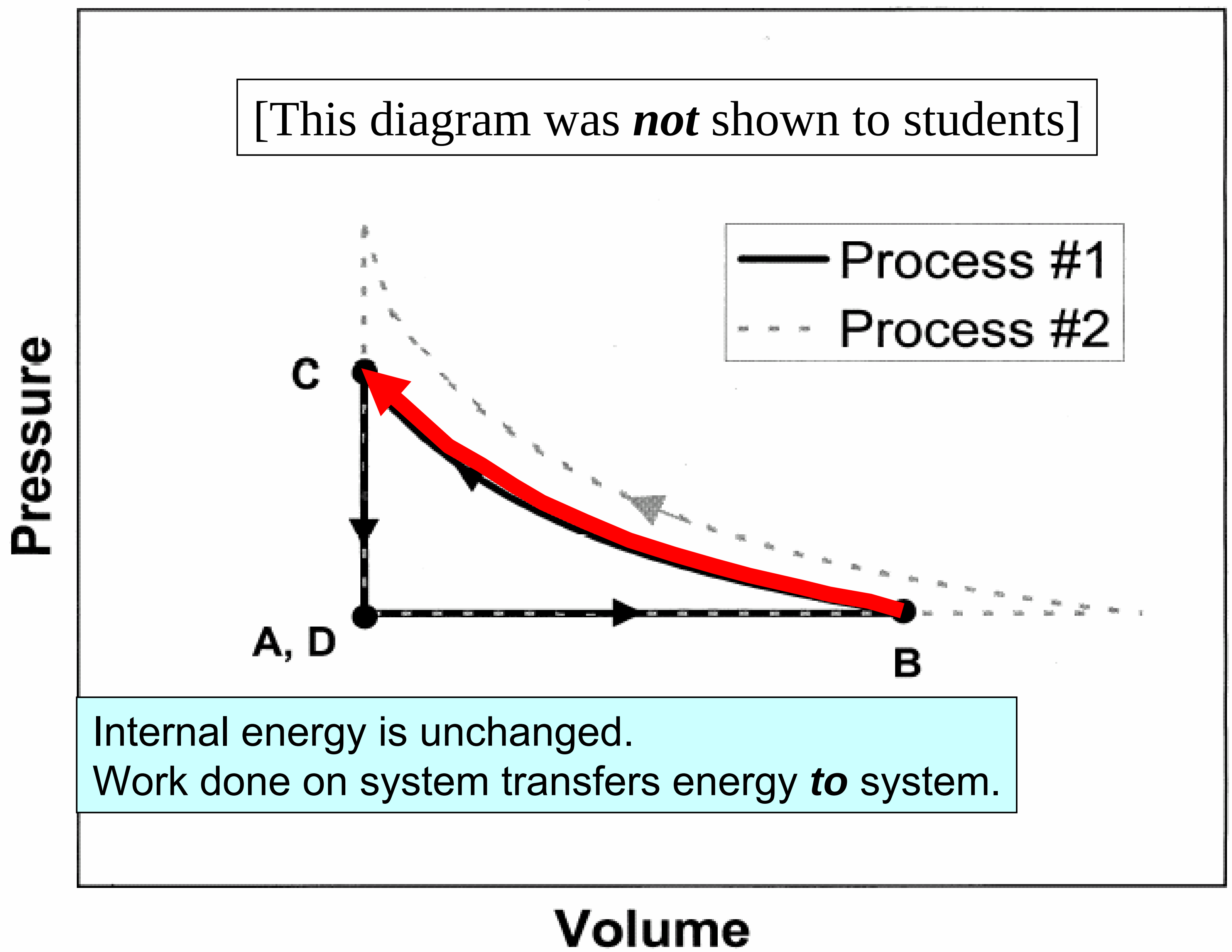


$\Delta T_{BC} = 0$

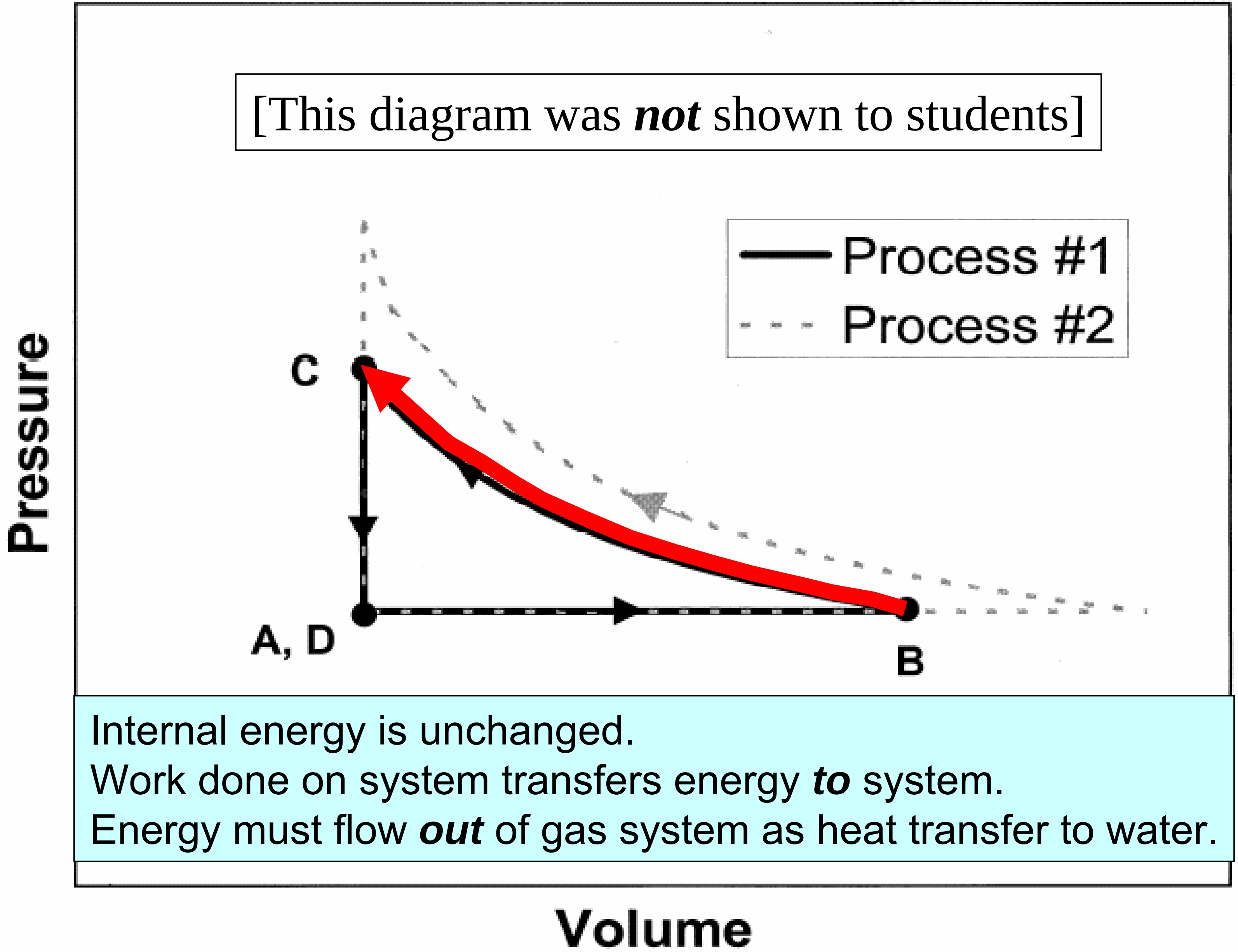
[This diagram was ***not*** shown to students]



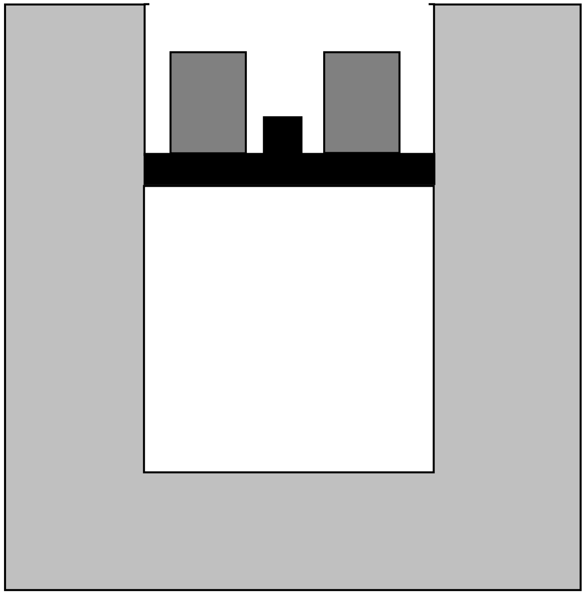
Internal energy is unchanged.


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

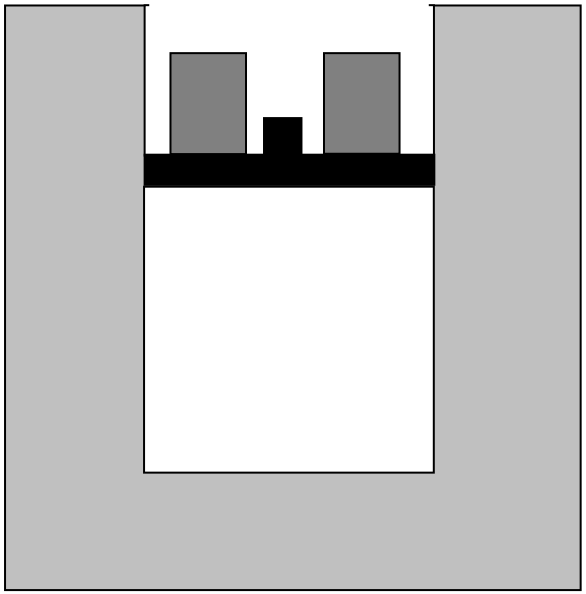
[This diagram was ***not*** shown to students]



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*."

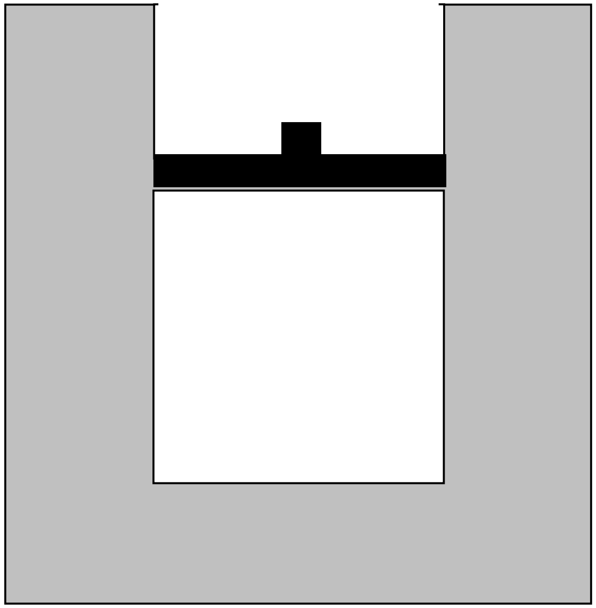
Misunderstanding of "thermal reservoir" concept, in which heat may be transferred to or from an entity that has practically unchanging temperature

Thermal Physics Students Shared Difficulties Manifested by Introductory Students

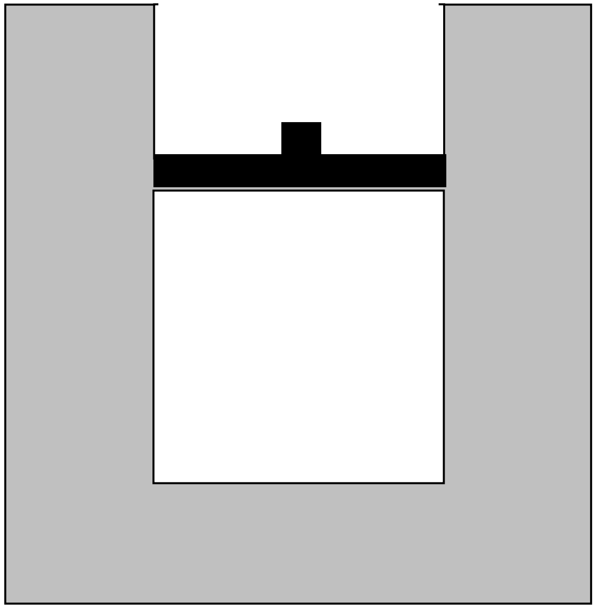
- Failed to recognize that total kinetic energy of ideal gas molecules does ***not*** change when temperature is held constant:
  - **Interview sample: 44%**
  - **2004 Thermal Physics students: 45%**

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

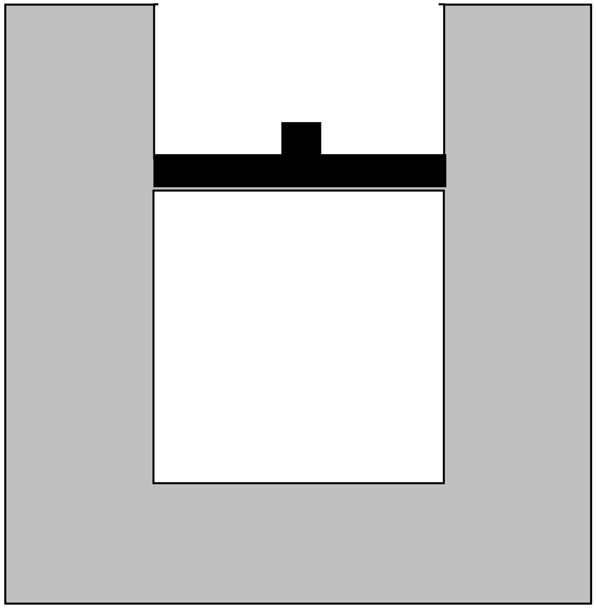
Now, the piston is locked into place so it *cannot move*, and the weights are removed from the piston.



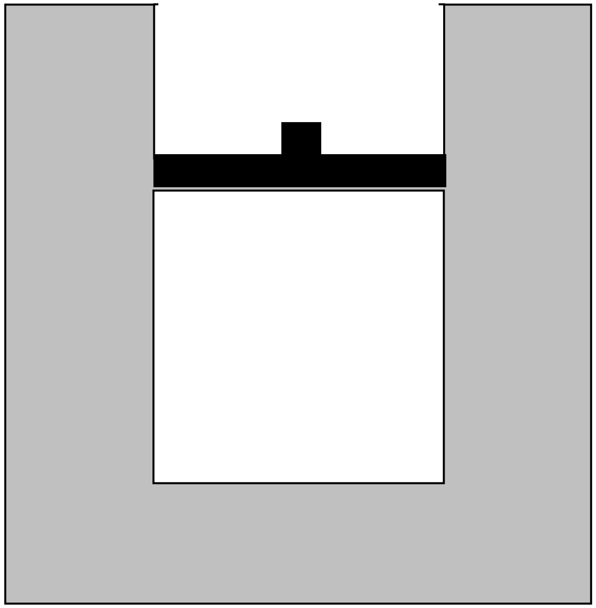
The system is left to sit in the room for many hours.

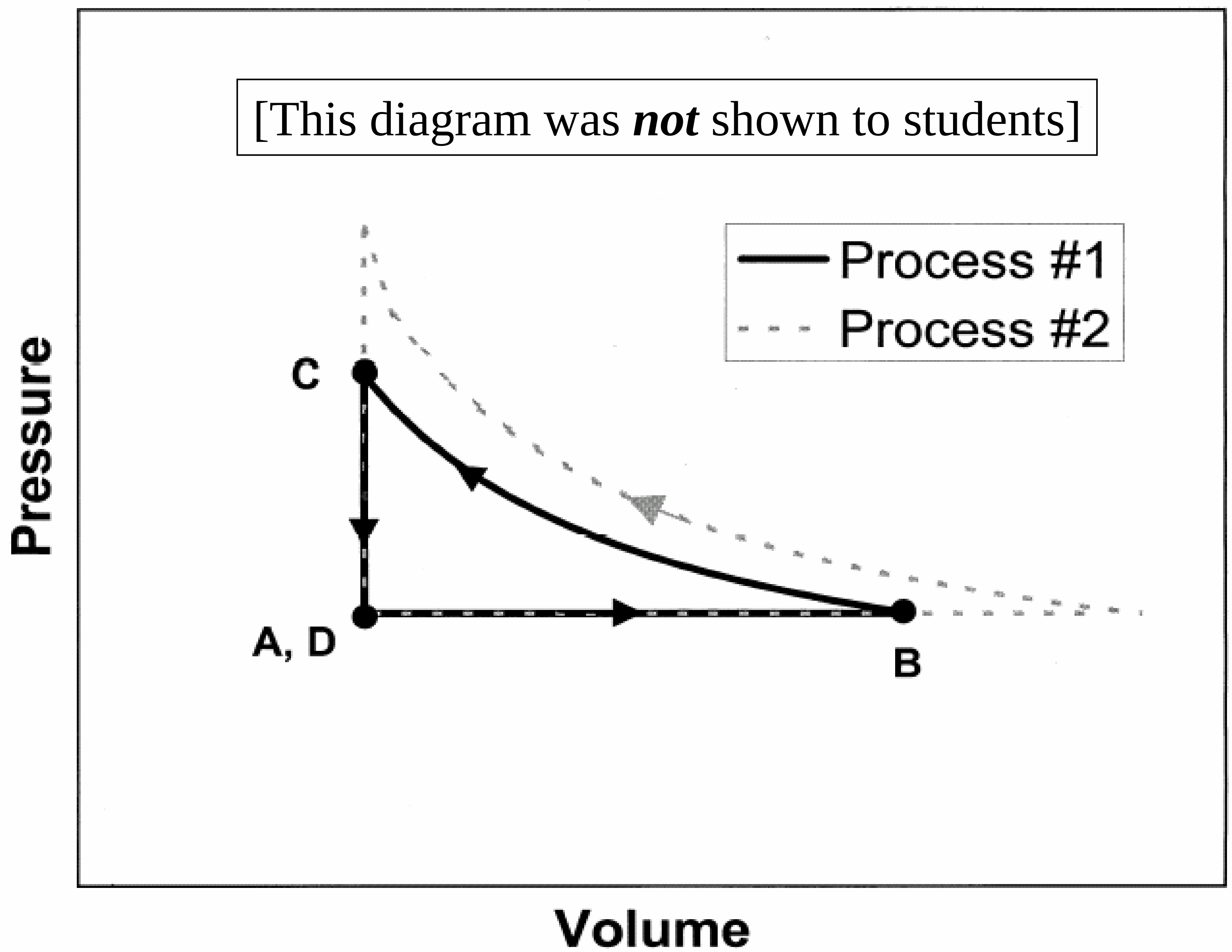


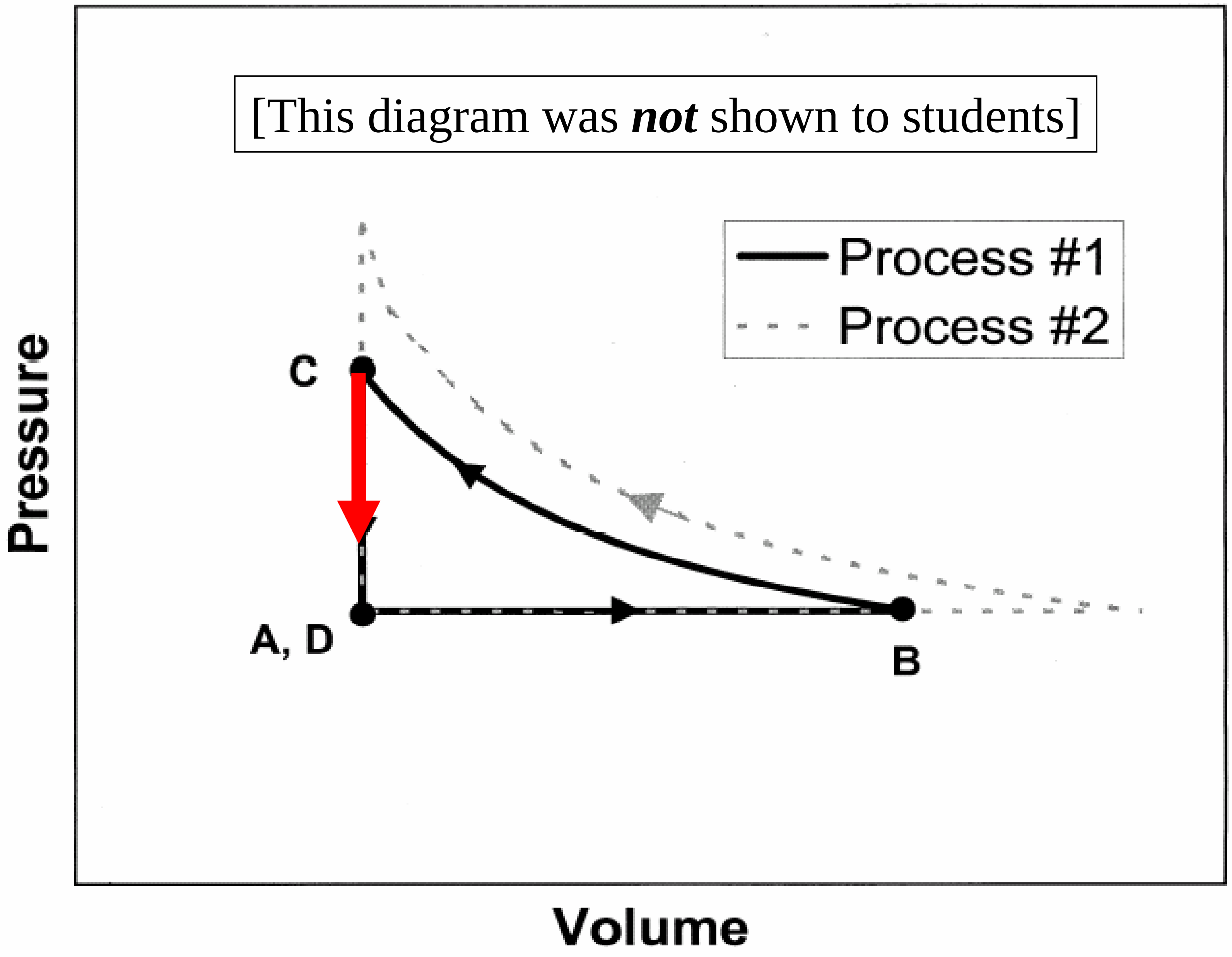
Eventually the entire system cools back down to the same room temperature it had at time ***A***.

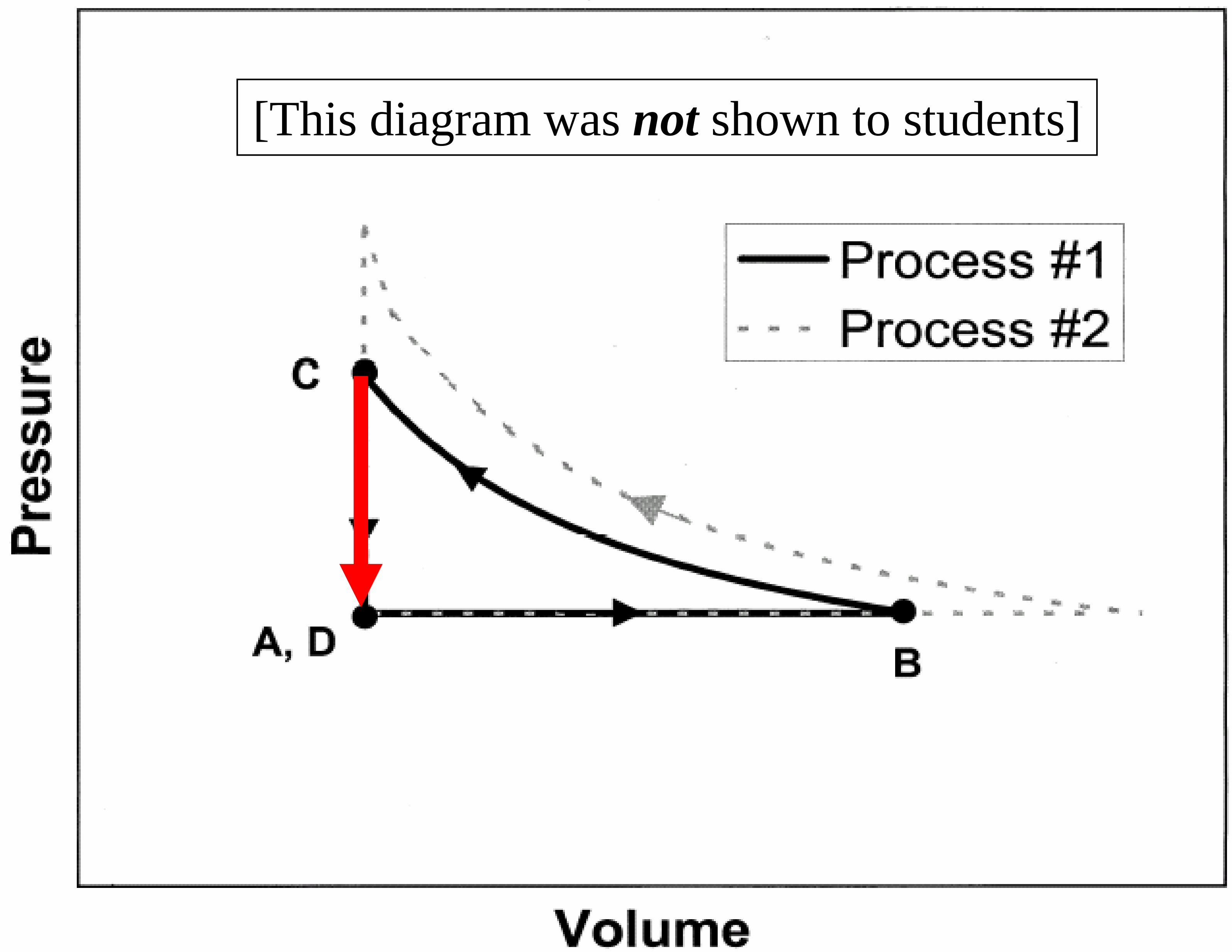


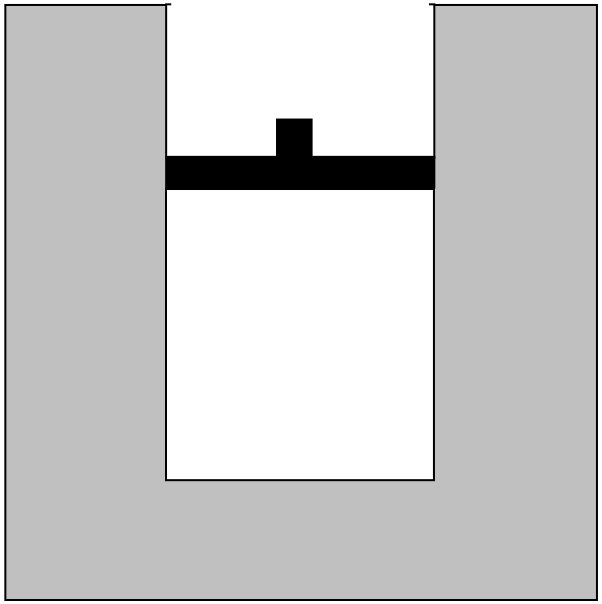
After cooling is complete, it is time ***D.***




[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

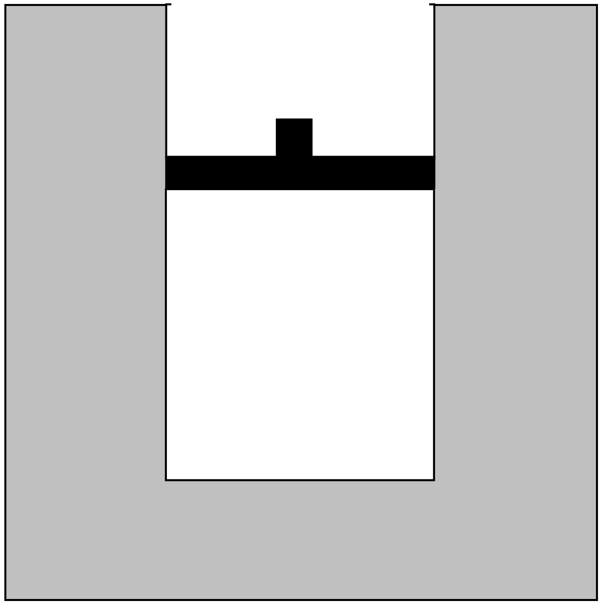

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



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?



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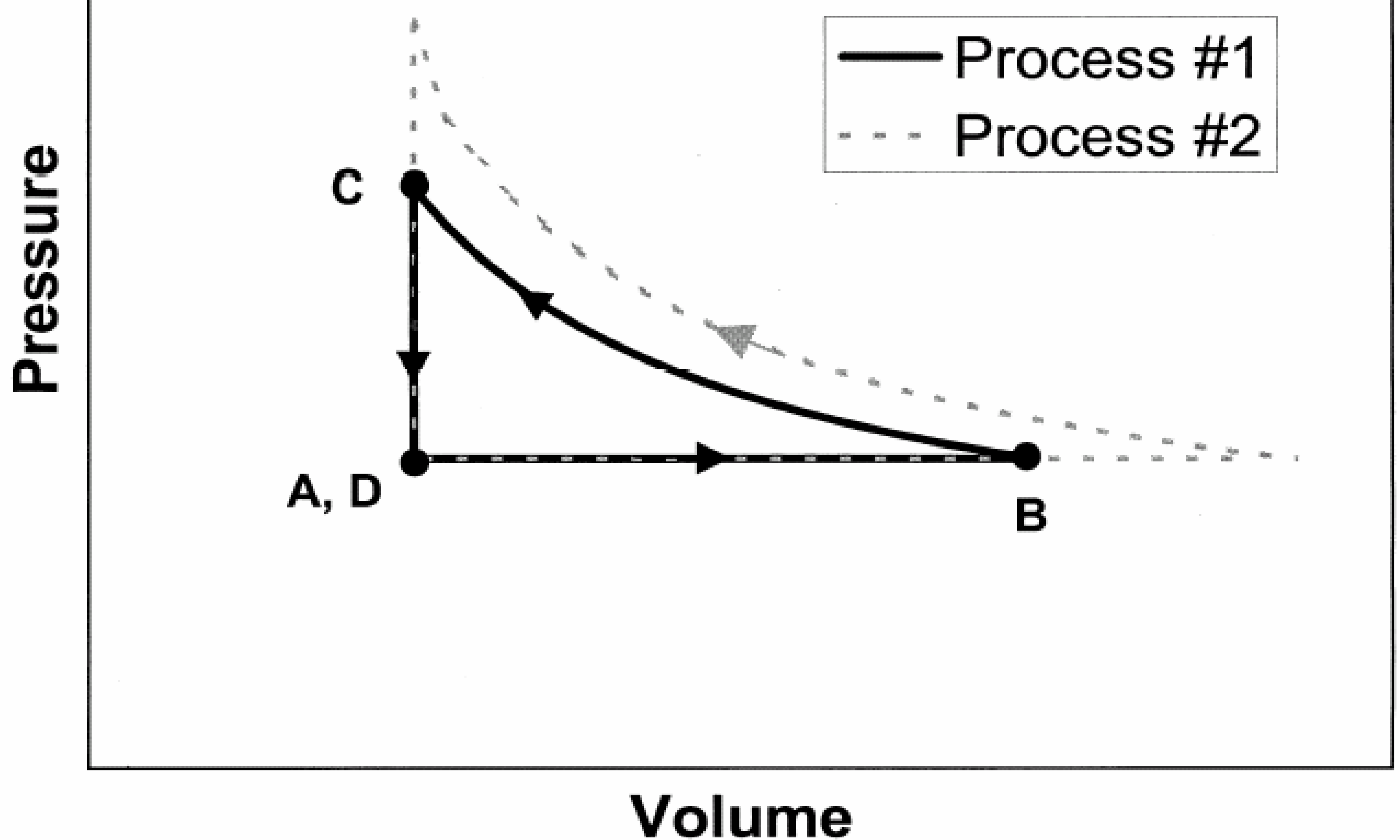
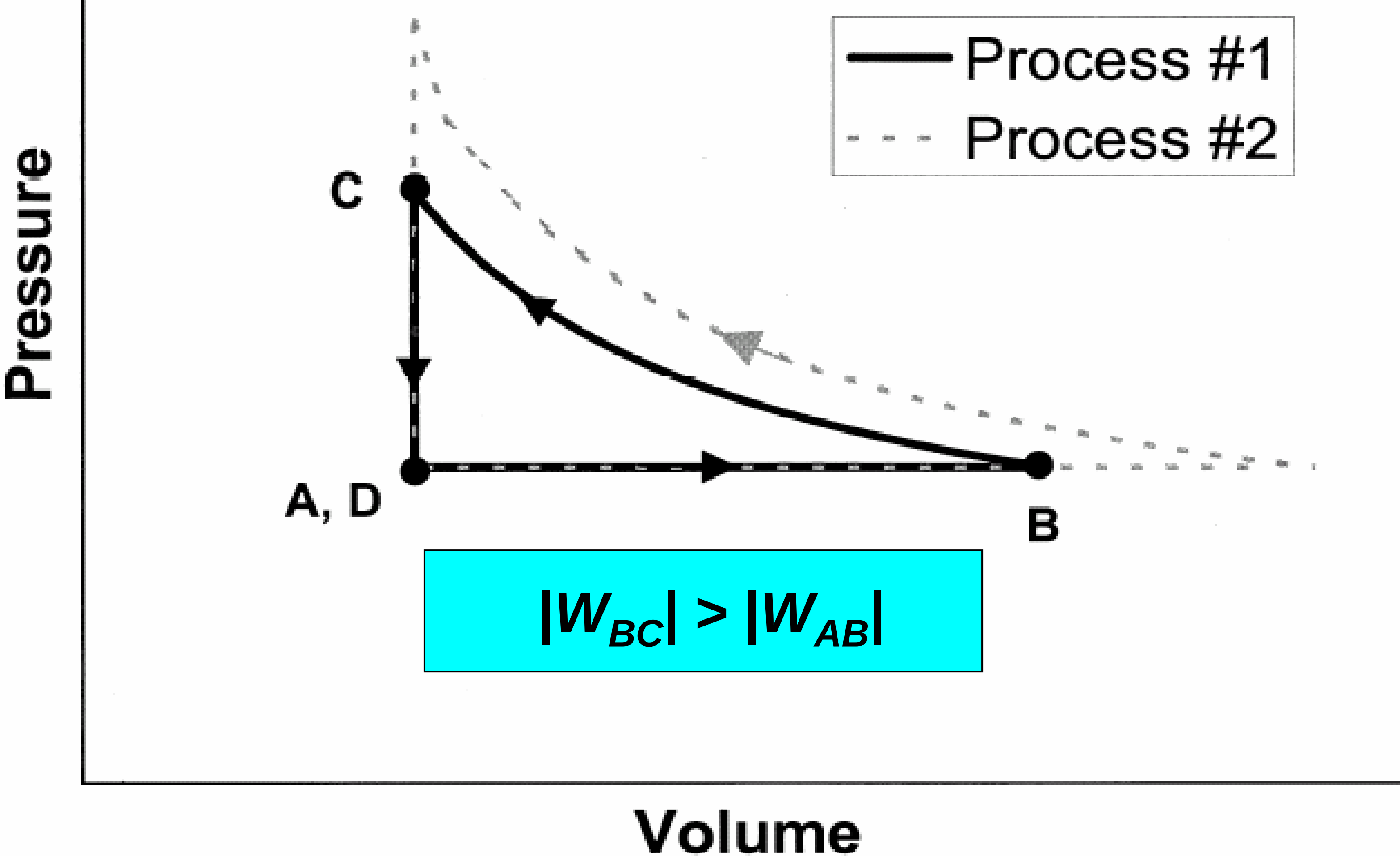
[This diagram was ***not*** shown to students]

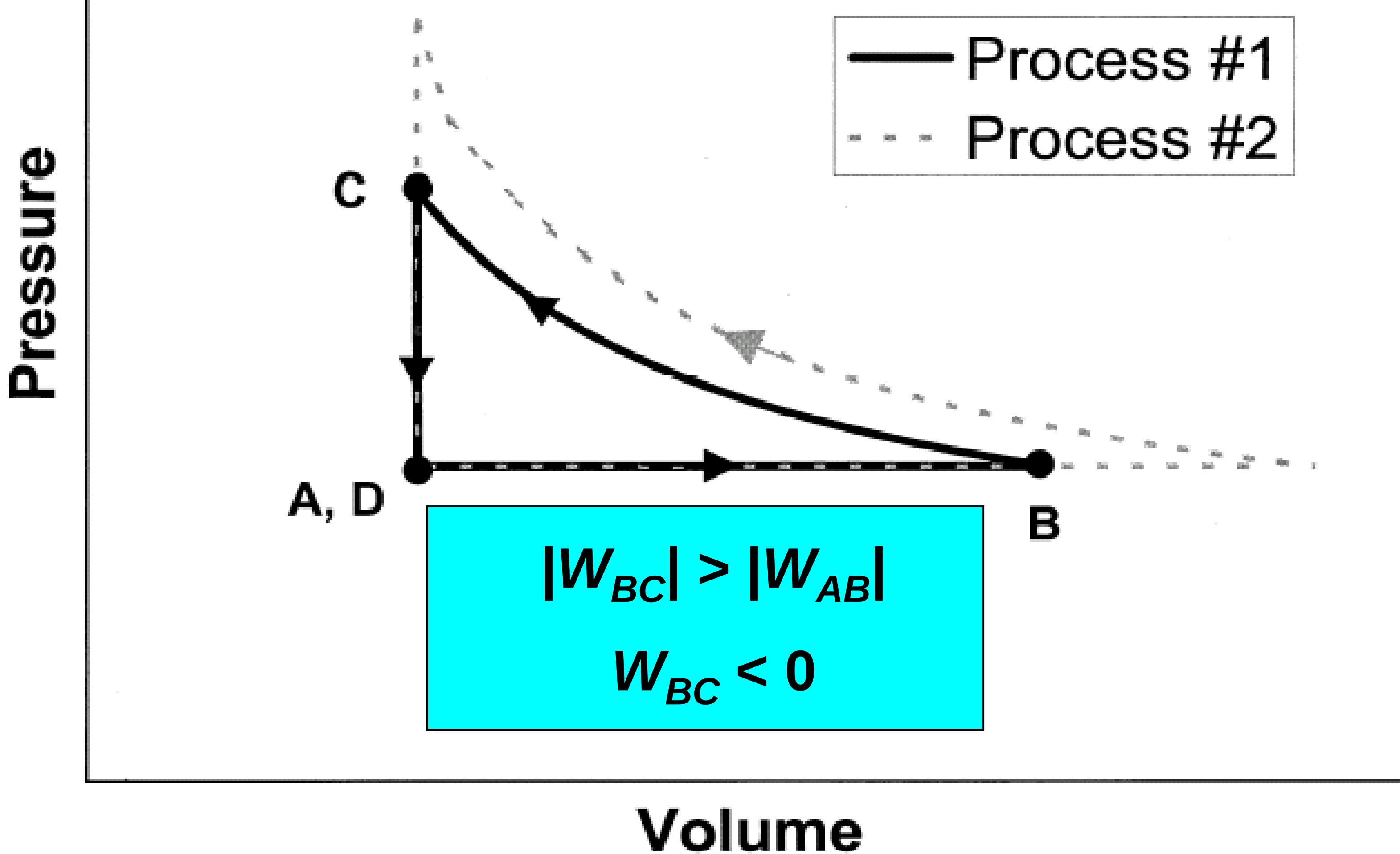


[This diagram was ***not*** shown to students]



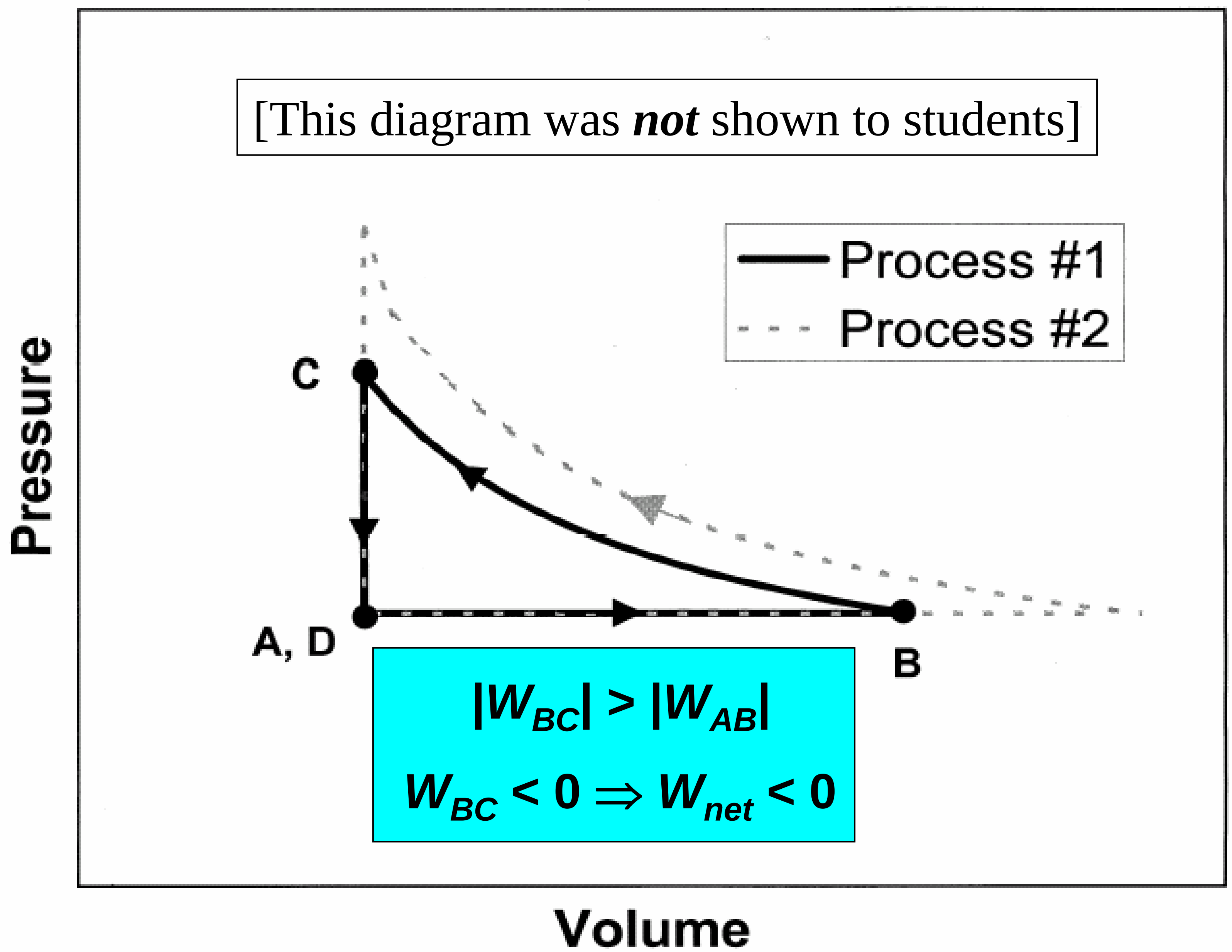
$|W_{BC}| > |W_{AB}|$

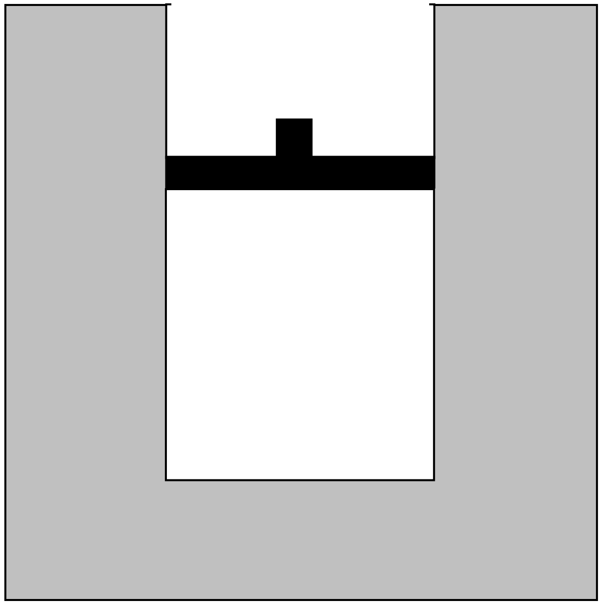
[This diagram was ***not*** shown to students]



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

$W_{BC} < 0$


[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



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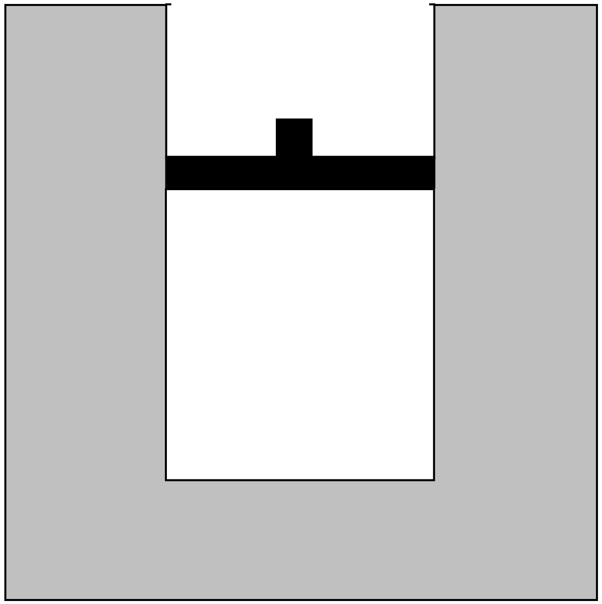

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(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or **(c) less than zero?**

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

Results on Question #6 (i)

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

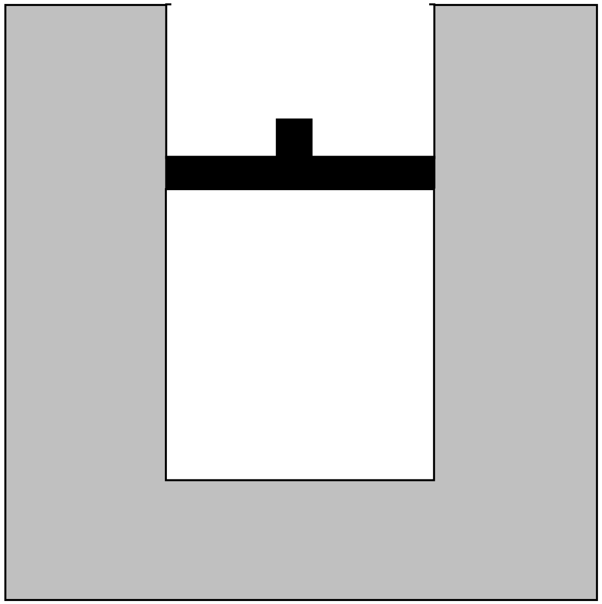
Interview sample *[post-test, N = 32]****: 19%***

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%***



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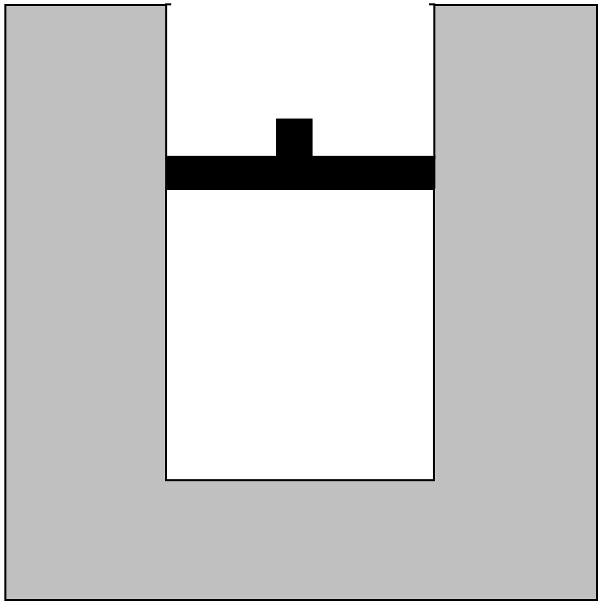

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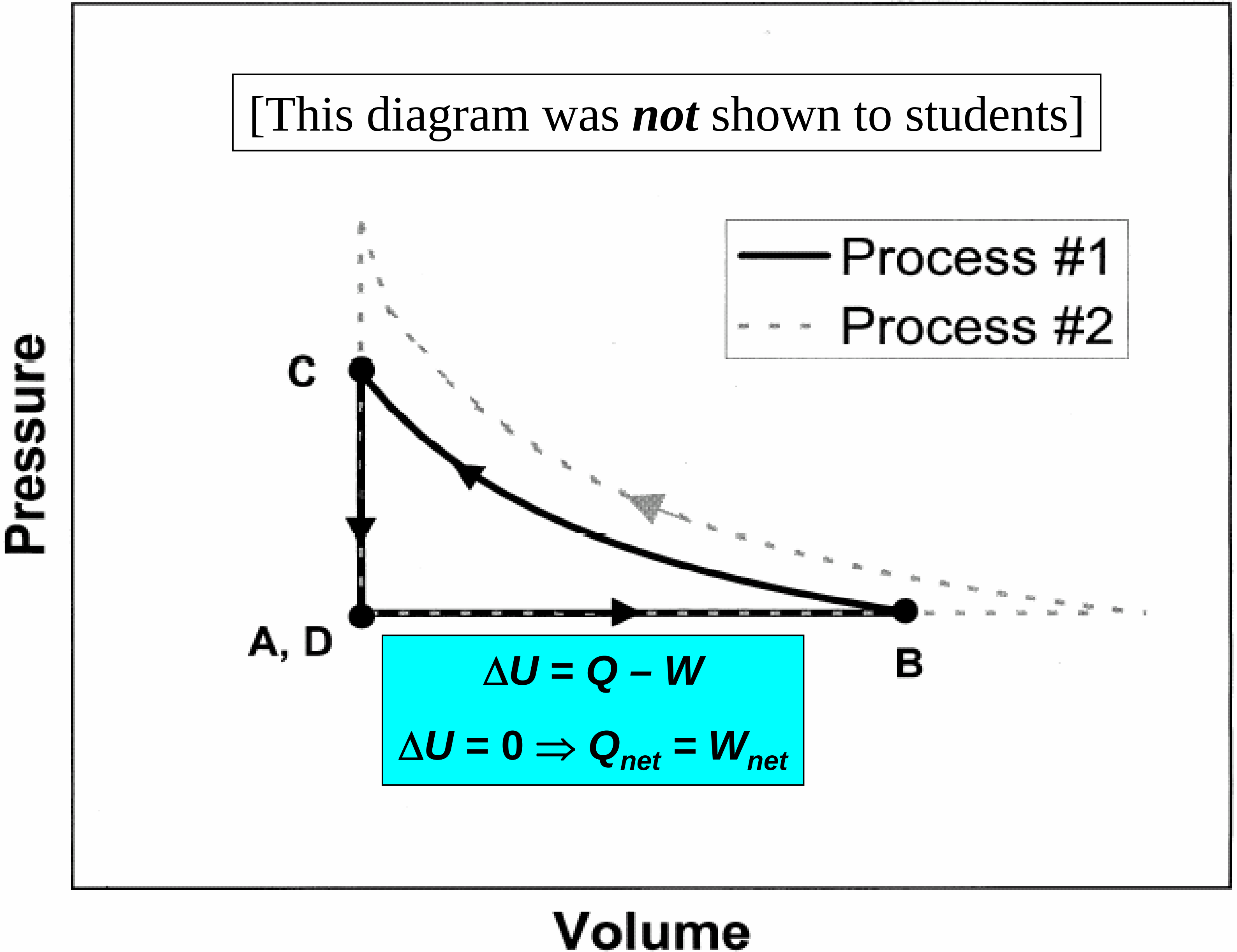
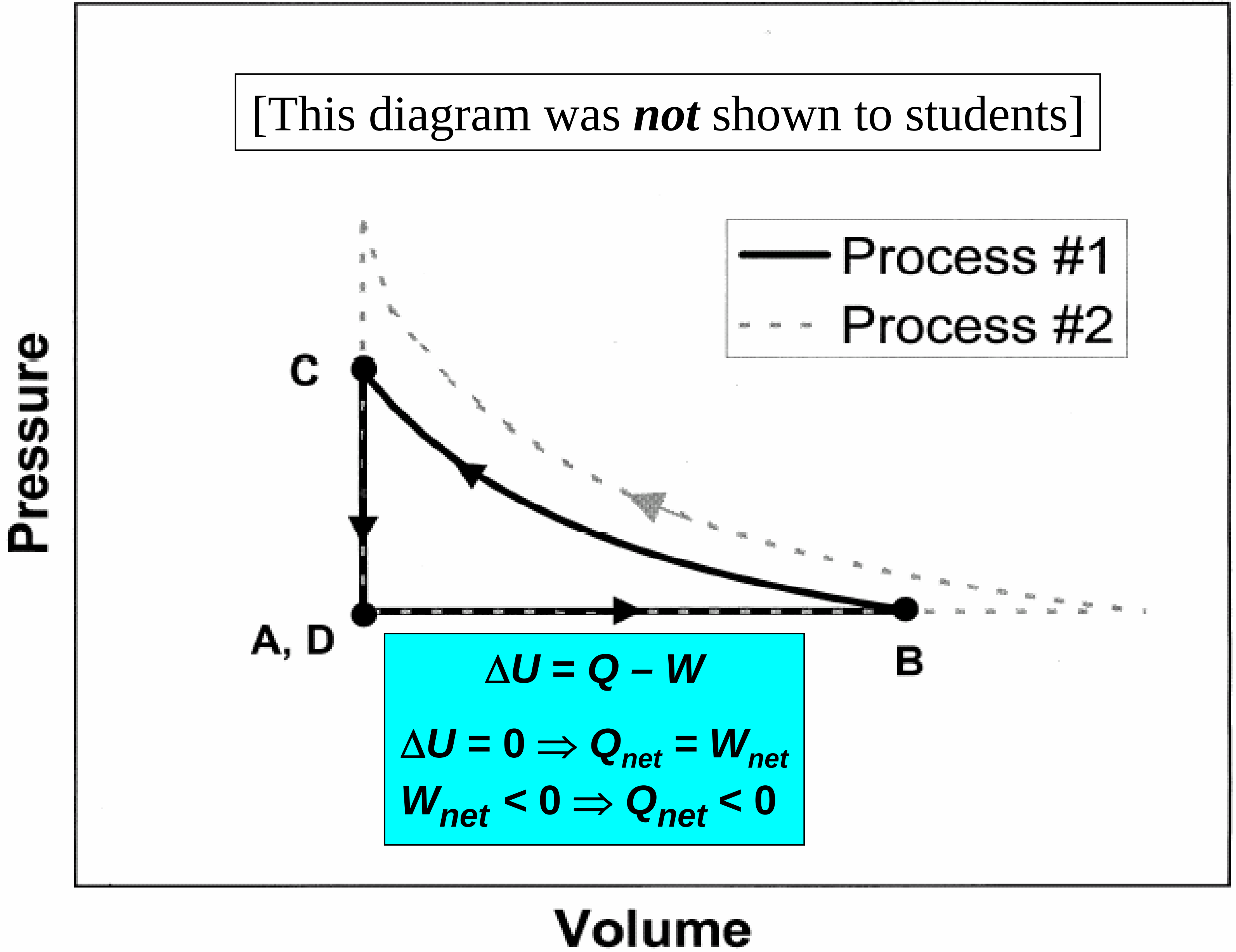
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

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

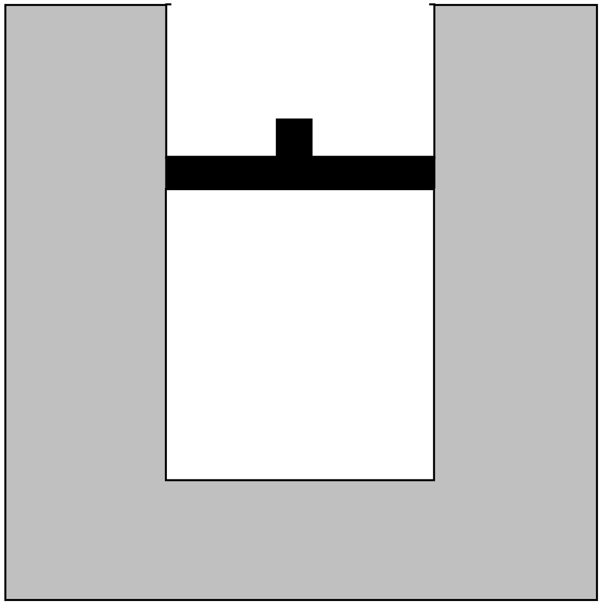
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

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

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



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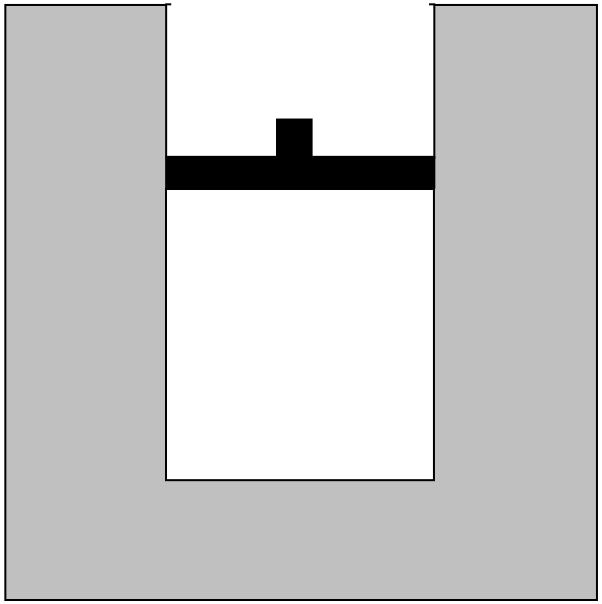

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(ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or **(c) less than zero?**

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.

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

- 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.

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}

…

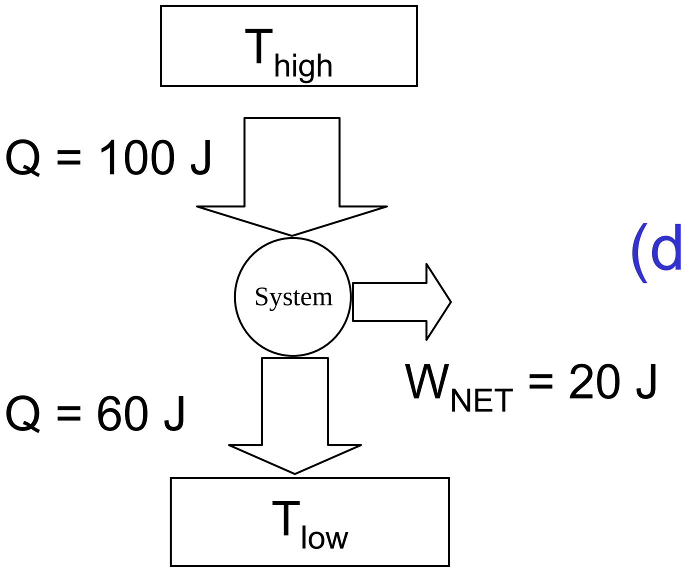
Consider a system composed of a fixed quantity of gas (not necessarily ideal) that undergoes a cyclic process in which the final state is the same as the initial state.

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.



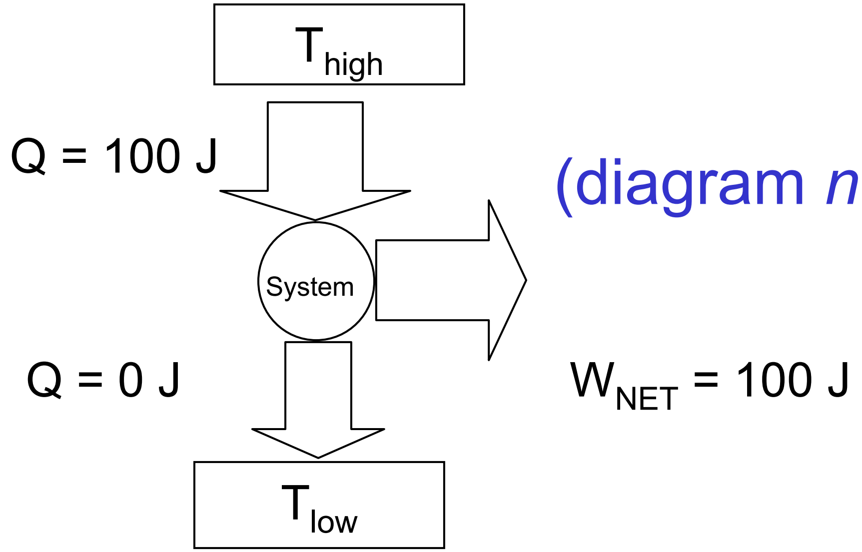
(diagram *not* given)

(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.

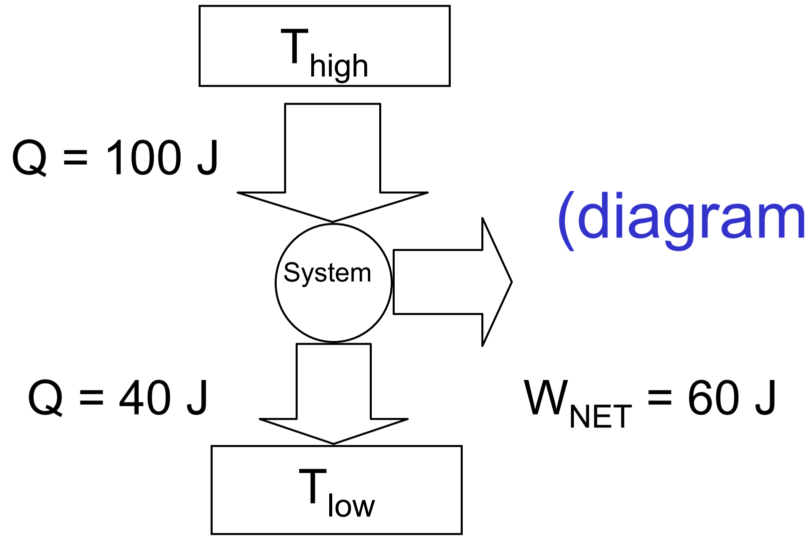
$$\boxed{\Rightarrow \eta_{reversible} = \frac{W}{Q_{in}} = \frac{40}{100} = 0.40 = \eta_{max}}$$

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 (in press)

Heat Engines: Post-Instruction

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

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

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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.

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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.)

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

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

$\boxed{\text{Cycle 2: heat transfer at high temperature is 300 J; heat transfer at low temperature is 60 J}}$

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

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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?

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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

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40% correct with correct explanation (N = 15)

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

Spontaneous Process Question

[Introductory-Course Version]

3. 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 **system** [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 **surroundings** [$S_{surroundings}$] *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 Question

[Correct Responses]				
S_{system}				
$S_{surroundings}$				
S_{total}				

Responses to Spontaneous Process Question

[Correct Responses]	2004-2006 Introductory Physics (Pretest) (N=1184)			
S_{system}				
$S_{surroundings}$				
S_{total}				

Responses to Spontaneous Process Question

[Correct Responses]	**2004-2006** **Introductory Physics** **(Pretest)** **(*N*=1184)**			
S_{system}	**40%**			
$S_{surroundings}$	**41%**			
S_{total}	**19%**			

Responses to Spontaneous Process Question

[Correct Responses]	**2005** **Introductory Physics** **(Posttest)** **(*N*=255)**			
S_{system}	**40%**			
$S_{surroundings}$	**39%**			
S_{total}	**30%**			

Responses to Spontaneous Process Question

[Correct Responses]	**2005** **Introductory Physics** **(Posttest)** **(N=255)**	**2004** **Thermal Physics** **(Pretest)** **(N=12)**		
S_{system}	**40%**	**50%**		
$S_{surroundings}$	**39%**	**50%**		
S_{total}	**30%**	**90%**		

Responses to Spontaneous Process Question

[Correct Responses]	2005 Introductory Physics (Posttest) (*N*=255)	2004 Thermal Physics (Pretest) (*N*=12)	2004 Thermal Physics (Post-Instruction Interviews) (*N*=12)	
S_{system}	40%	50%		
$S_{surroundings}$	39%	50%		
S_{total}	30%	90%		

Responses to Spontaneous Process Question

[Correct Responses]	2005 Introductory Physics (Posttest) (*N*=255)	2004 Thermal Physics (Pretest) (*N*=12)	2004 Thermal Physics (Post-Instruction Interviews) (*N*=12)	
			correct	
S_{system}	40%	50%	75%	
$S_{surroundings}$	39%	50%	75%	
S_{total}	30%	90%	100%	

Responses to Spontaneous Process Question

[Correct Responses]	2005 Introductory Physics (Posttest) (*N*=255)	2004 Thermal Physics (Pretest) (*N*=12)	2004 Thermal Physics (Post-Instruction Interviews) (*N*=12)	
			correct	with correct explanation
S_{system}	40%	50%	75%	65%
$S_{surroundings}$	39%	50%	75%	75%
S_{total}	30%	90%	100%	100%

Responses to Spontaneous Process Question

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S_{system}	40%	50%	75%	65%
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S_{total}	30%	90%	100%	100%

Thermal Physics Students' Thinking on Spontaneous Processes

- Readily accept that "entropy of universe increases"
  - in contrast to introductory students
- Tendency to assume that "system entropy" must *always* increase
  - similar to thinking of introductory students

Some Strategies for Instruction

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- Develop and emphasize concept of work as an energy-transfer mechanism in thermodynamics context.

Some Strategies for Instruction

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

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.

Implementation of Instructional Model

“Elicit, Confront, Resolve” (U. Washington)

- Pose questions to students in which they tend to encounter common conceptual difficulties
- Allow students to commit themselves to a response that reflects conceptual difficulty
- Guide students along reasoning track that bears on same concept
- Direct students to compare responses and resolve any discrepancies

Implementation of Instructional Model

"Elicit, Confront, Resolve" (U. Washington)

→ *One of the central tasks in curriculum reform is development of "Guided Inquiry" worksheets*

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  - *emphasis on qualitative reasoning*

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- Worksheets consist of sequences of closely linked problems and questions
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- Worksheets designed for use by students working together in small groups (3-4 students each)

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One of the central tasks in curriculum reform is development of "Guided Inquiry" worksheets

- Worksheets consist of sequences of closely linked problems and questions
  - *focus on conceptual difficulties identified through research*
  - *emphasis on qualitative reasoning*
- Worksheets designed for use by students working together in small groups (3-4 students each)
- Instructors provide guidance through "Socratic" questioning

Example: Entropy Worksheet

(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 wire)
  - Does total energy change during process?
  - Does total entropy change during process?

- 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

- Examine situation when $\Delta T \rightarrow 0$ to see that $\Delta S \rightarrow 0$ and process approaches "reversible" idealization.

Thermodynamics Curricular Materials

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

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

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.