Physics Education Research and its Impact on Classroom Instruction

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Collaborators

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- Jack Dostal (ISU, M.S. 2005)
- Ngoc-Loan Nguyen (ISU, M.S. 2003)
- Warren Christensen (ISU Ph.D. student)

Funding

- NSF Division of Undergraduate Education
- NSF Division of Physics

Outline

Physics Education as a Research Problem

- Goals and methods of PER
- Some specific issues

Research-Based Instructional Methods

- Principles of research-based instruction
- Instruction in large classes

Research-Based Curriculum Development

- A “model” problem: law of gravitation
- Student reasoning in thermodynamics

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Physics Education As a Research Problem

Within the past 25 years, physicists have begun to treat the teaching and learning of physics as a research problem

- Systematic observation and data collection; reproducible experiments
- Identification and control of variables
- In-depth probing and analysis of students' thinking

Physics Education Research ("PER")

Goals of PER

- Improve effectiveness and efficiency of physics instruction
  - guide students to learn concepts in greater depth
- Develop instructional methods and materials that address obstacles which impede learning
- Critically assess and refine instructional innovations

Methods of PER

- Develop and test diagnostic instruments that assess student understanding
- Probe students’ thinking through analysis of written and verbal explanations of their reasoning, supplemented by multiple-choice diagnostics
- Assess learning through measures derived from pre- and post-instruction testing

What PER Can NOT Do

- Determine “philosophical” approach toward undergraduate education
  - e.g., focus on majority of students, or on subgroup?
- Specify the goals of instruction in particular learning environments
  - proper balance among “concepts,” problem-solving, etc.

Active PER Groups in Ph.D.-granting Physics Departments

> 12 yrs old	8-12 yrs old	< 8 yrs old
*U. Washington	U. Maine	Oregon State U.
*Kansas State U.	Montana State U.	City Col. N.Y.
*Ohio State U.	U. Arkansas	Texas Tech U.
*North Carolina State U.	U. Virginia	Florida International U.
*U. Maryland		U. Colorado
*U. Minnesota		U. Illinois
*San Diego State U. [joint with U.C.S.D.]		U. Pittsburgh
*Arizona State U.		Rutgers U.
U. Mass., Amherst		Western Michigan U.
U. Oregon		Worcester Polytechnic Inst.
U. California, Davis		New Mexico State U.
		U. Arizona

*leading producers of Ph.D.'s

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Some Specific Issues

Many (if not most) students:

- develop weak ***qualitative*** understanding of concepts
  - don’t use qualitative analysis in problem solving
  - lacking quantitative problem solution, can’t reason “physically”

- lack a **“*functional*”** understanding of concepts (which would allow problem solving in unfamiliar contexts)

But … *some* students learn efficiently . . .

- Highly successful physics students are ***"active learners."***
  - they continuously probe their own understanding

    [*pose their own questions; scrutinize implicit assumptions; examine varied contexts; etc.*]
  - they are sensitive to areas of confusion, and have the confidence to confront them directly
- Majority of introductory students are unable to do efficient active learning on their own: they don't know "which questions they need to ask"
  - they require considerable assistance from instructors, aided by appropriate curricular materials

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Research in physics education suggests that:

- “Teaching by telling” has only limited effectiveness
  - *listening and note-taking have relatively little impact*

- Problem-solving activities with rapid feedback yield improved learning gains

- Eliciting and addressing common conceptual difficulties improves learning and retention

Active-Learning Pedagogy
(“*Interactive Engagement*”)

- problem-solving activities during class time
  - student group work
  - frequent question-and-answer exchanges with instructor

- “*guided-inquiry*” methodology: guide students through structured series of problems and exercises

Goal: Guide students to “figure things out for themselves” as much as possible

Key Themes of Research-Based Instruction

- Emphasize qualitative, non-numerical questions to reduce unthoughtful “plug and chug.”

- Make extensive use of multiple representations to deepen understanding.

  (Graphs, diagrams, words, simulations, animations, etc.)

- Require students to *explain their reasoning* (verbally or in writing) to more clearly expose their thought processes.

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Active Learning in Large Physics Classes

- **De-emphasis of lecturing**; Instead, ask students to respond to questions targeted at known difficulties.

- Use of classroom communication systems to obtain **instantaneous feedback** from entire class.

- Cooperative **group work** using research-based free-response worksheets

Goal: *Transform large-class learning environment into "office" learning environment (i.e., instructor + one or two students)*

“Fully Interactive” Physics Lecture

DEM and K. Manivannan, Am. J. Phys. ***70,*** *639 (2002)*

- Use structured sequences of multiple-choice questions, focused on specific concept: small conceptual “step size”

- Use student response system to obtain instantaneous responses from all students simultaneously (e.g., “flash cards”)

Results of Assessment

- Learning gains on qualitative problems are well above national norms for students in traditional courses.
- Performance on quantitative problems is comparable to (or slightly better than) that of students in traditional courses.
- Typical of other research-based instructional methods.

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Research-Based Curriculum Development

- Investigate student learning with standard instruction; probe learning difficulties
- Develop new materials based on research
- Test and modify materials
- Iterate as needed

Addressing Learning Difficulties: A Model Problem

Student Concepts of Gravitation

[Jack Dostal and DEM]

Addressing Learning Difficulties: A Model Problem

Student Concepts of Gravitation

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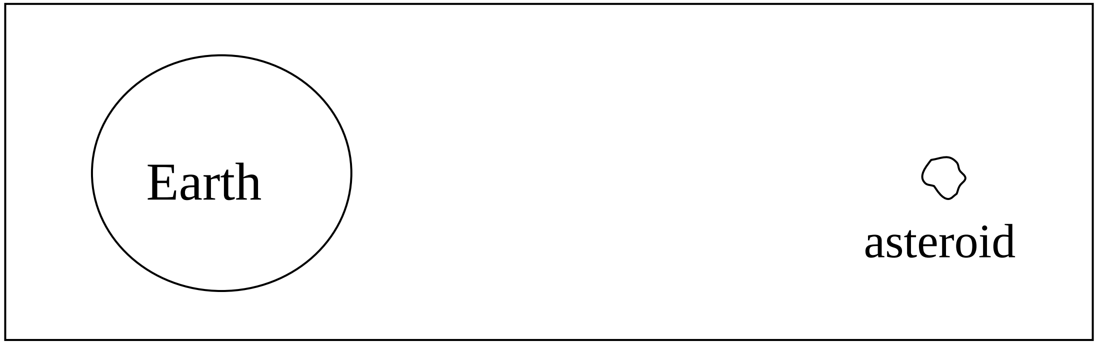
- 10-item free-response diagnostic administered to over 2000 ISU students during 1999-2000.
  - *Newton's third law in context of gravity, inverse-square law, etc.*

- Worksheets developed to address learning difficulties; tested in calculus-based physics course Fall 1999

Example: Newton's Third Law in the Context of Gravity



Is the magnitude of the force exerted **by the asteroid on the Earth** *larger than, smaller than, or the same as the magnitude of the force exerted* **by the Earth on the asteroid?** *Explain the reasoning for your choice.*

[Presented during first week of class to all students taking calculus-based introductory physics at ISU during Fall 1999.]

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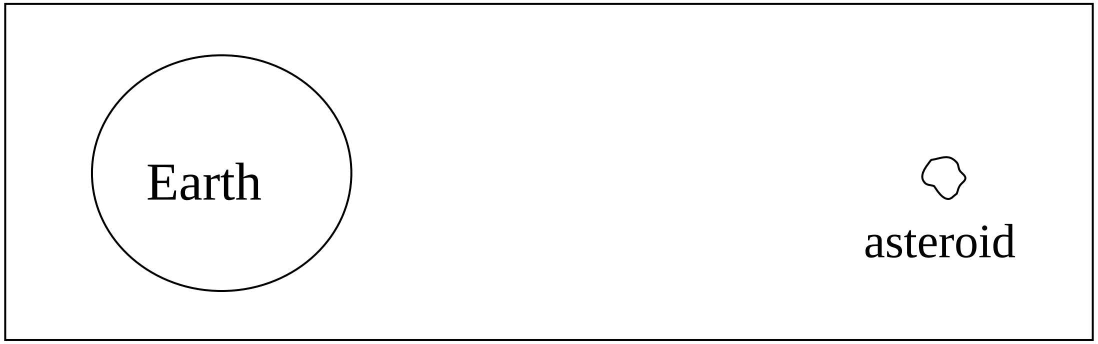

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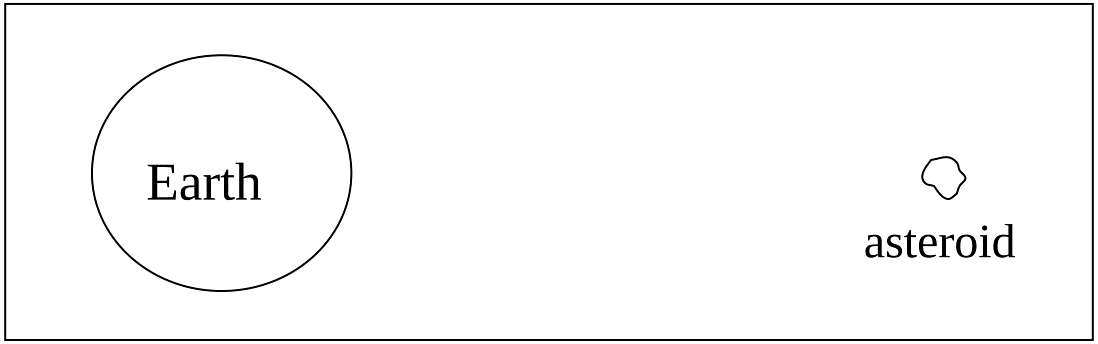

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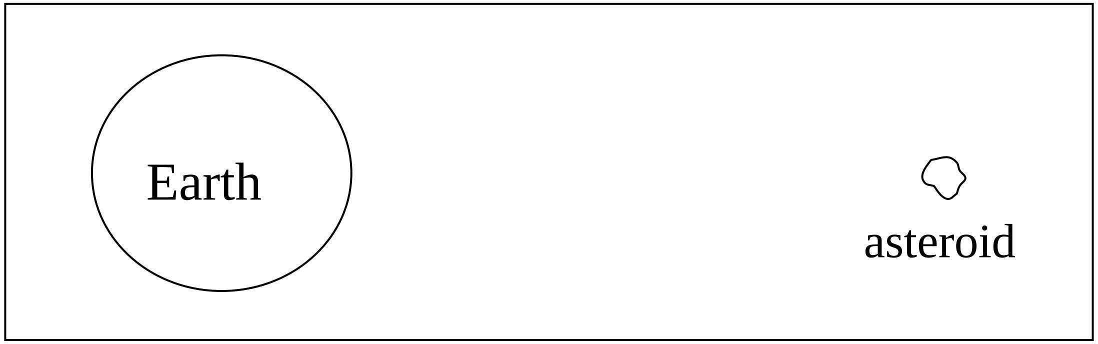

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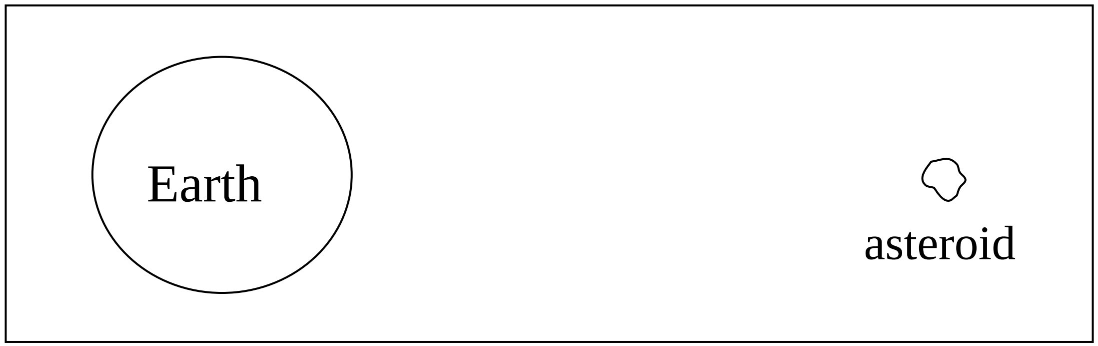

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Most students claim that Earth exerts greater force because it is larger

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*

Implementation of Instructional Model

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

→ *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: Gravitation Worksheet

(Jack Dostal and DEM)

- Design based on research, as well as instructional experience
- Targeted at difficulties with Newton's third law, and with use of proportional reasoning in inverse-square force law

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Physics 221

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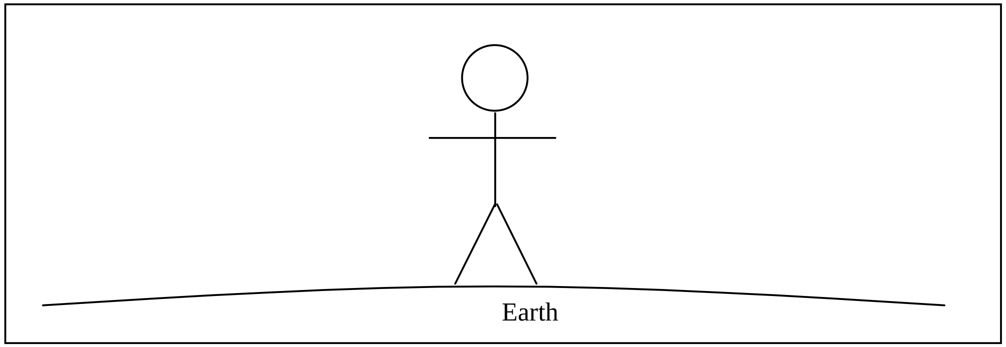

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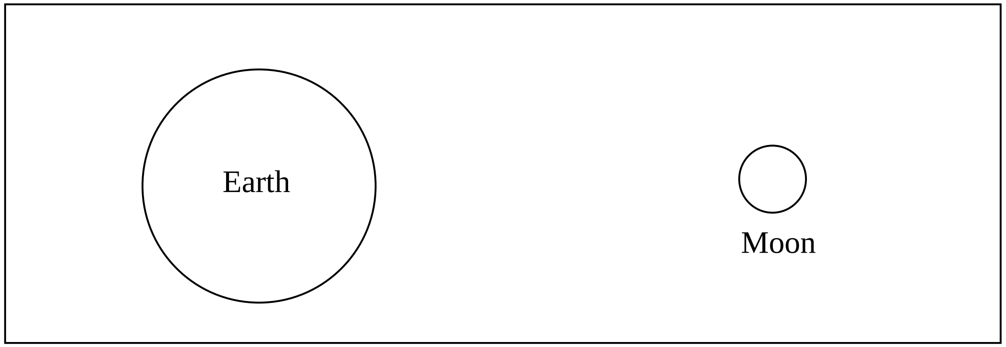

c) Now, in the same picture (above), draw an arrow which represents the force exerted ***by*** the Moon ***on*** the Earth. Label this arrow **(c)**. Remember to draw the arrow with the correct length and direction as compared to the arrow you drew in **(b)**.

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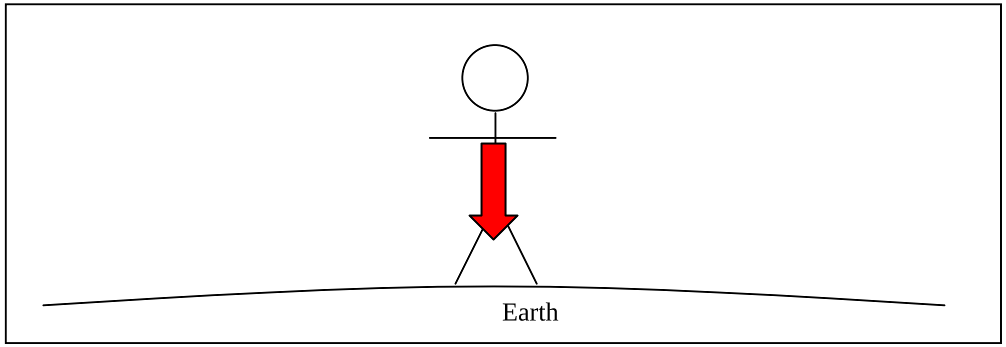

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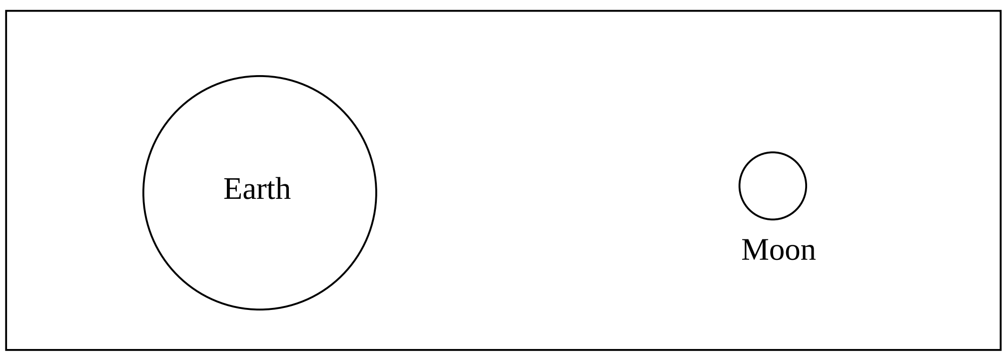

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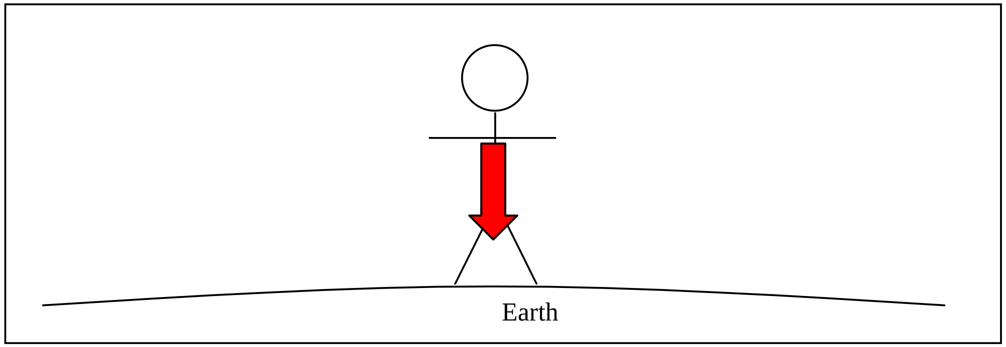

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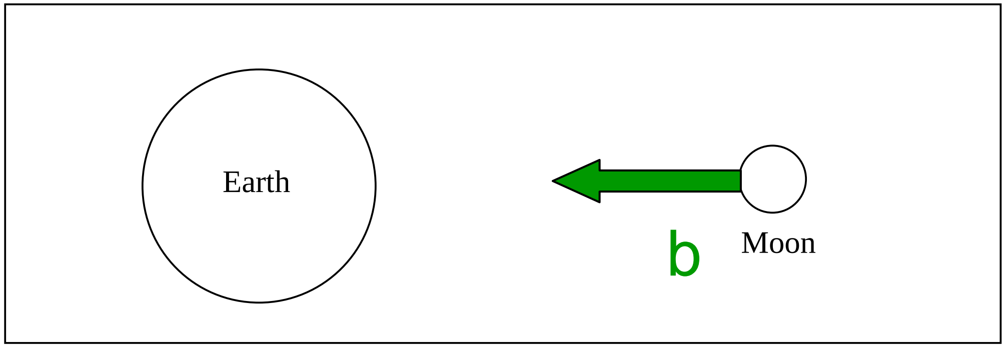

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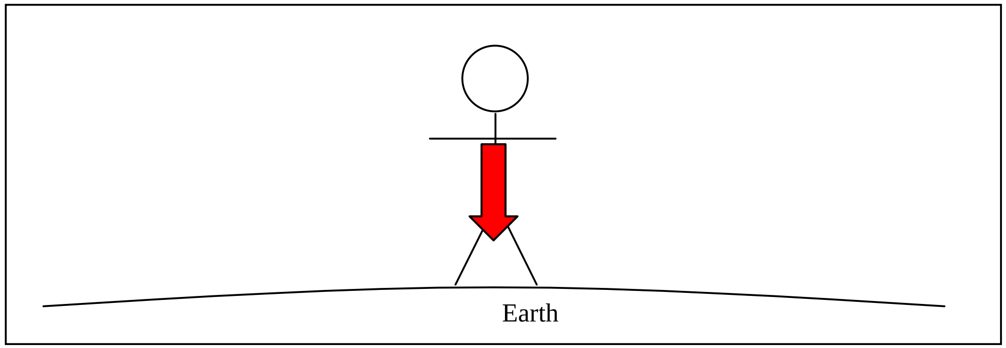

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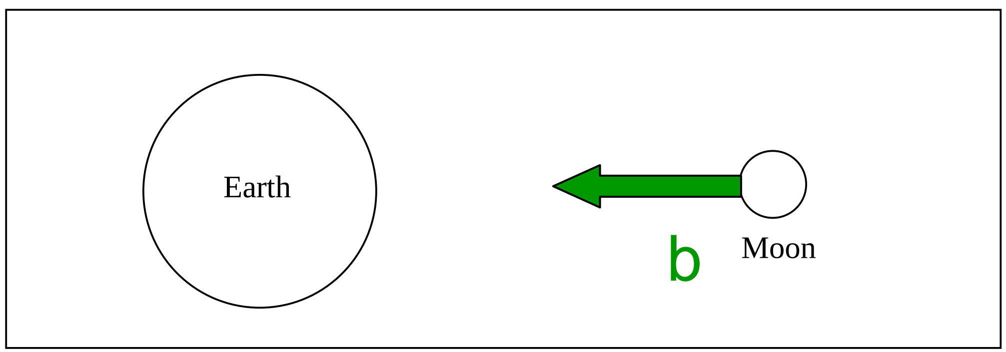

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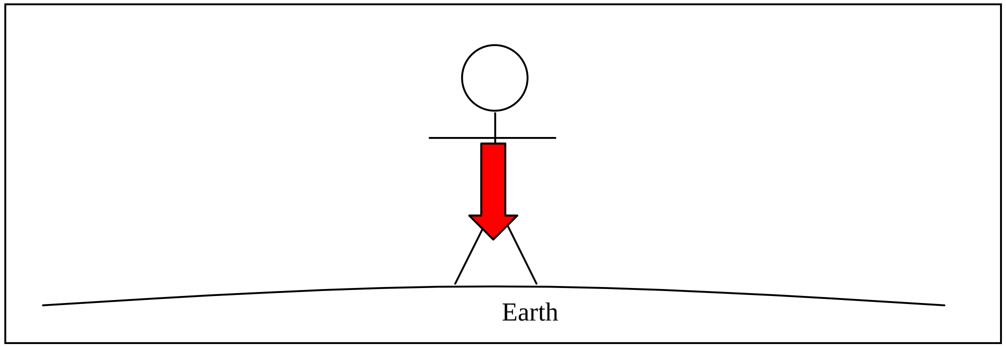

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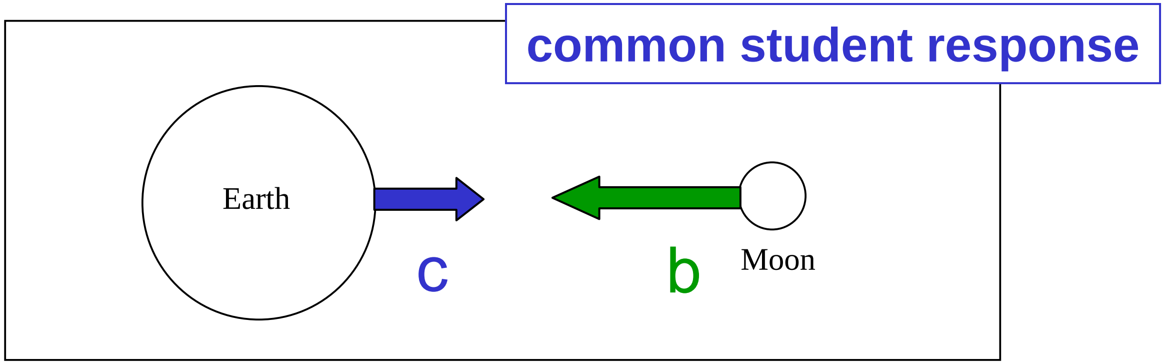

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g) Look at your answers for (e) and (f). Are they the same?

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$$F_b = G\frac{M_e M_m}{r^2}$$

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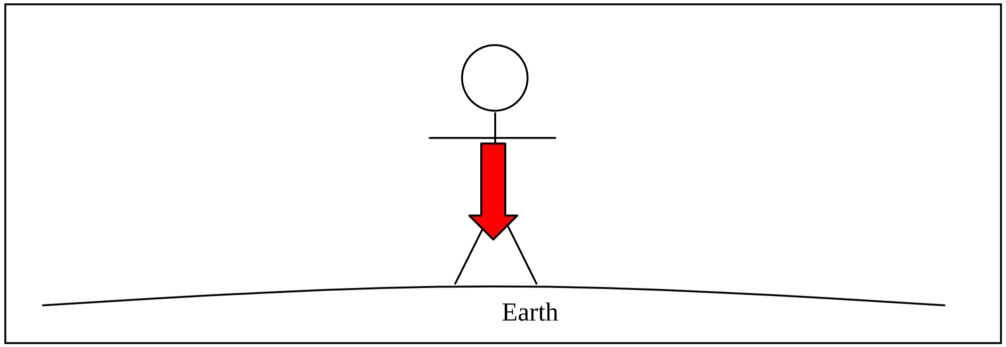

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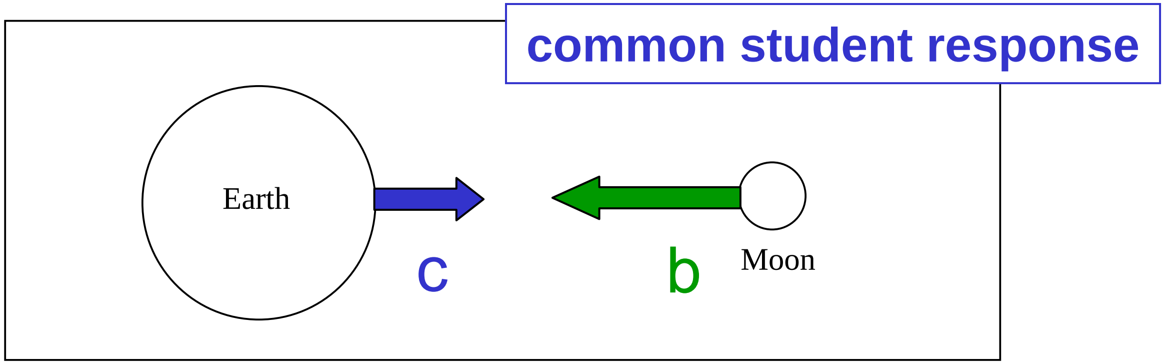

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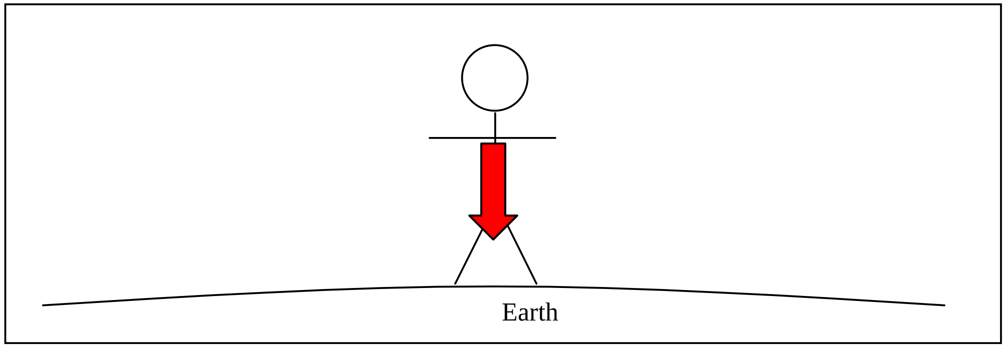

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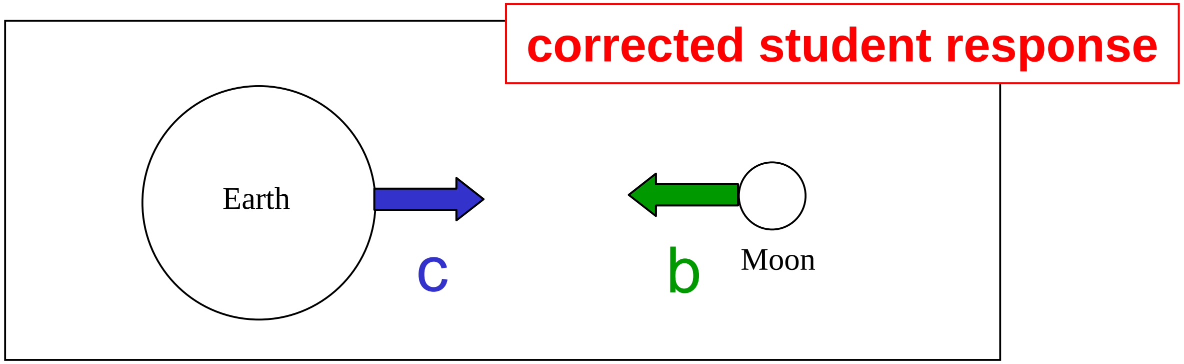

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The rings of the planet Saturn are composed of millions of chunks of icy debris. Consider a chunk of ice in one of Saturn's rings. Which of the following statements is true?

A. The gravitational force exerted by the chunk of ice on Saturn is **greater than** the gravitational force exerted by Saturn on the chunk of ice.

B. The gravitational force exerted by the chunk of ice on Saturn is **the same magnitude as** the gravitational force exerted by Saturn on the chunk of ice.

C. The gravitational force exerted by the chunk of ice on Saturn is **nonzero, and less than** the gravitational force exerted by Saturn on the chunk of ice.

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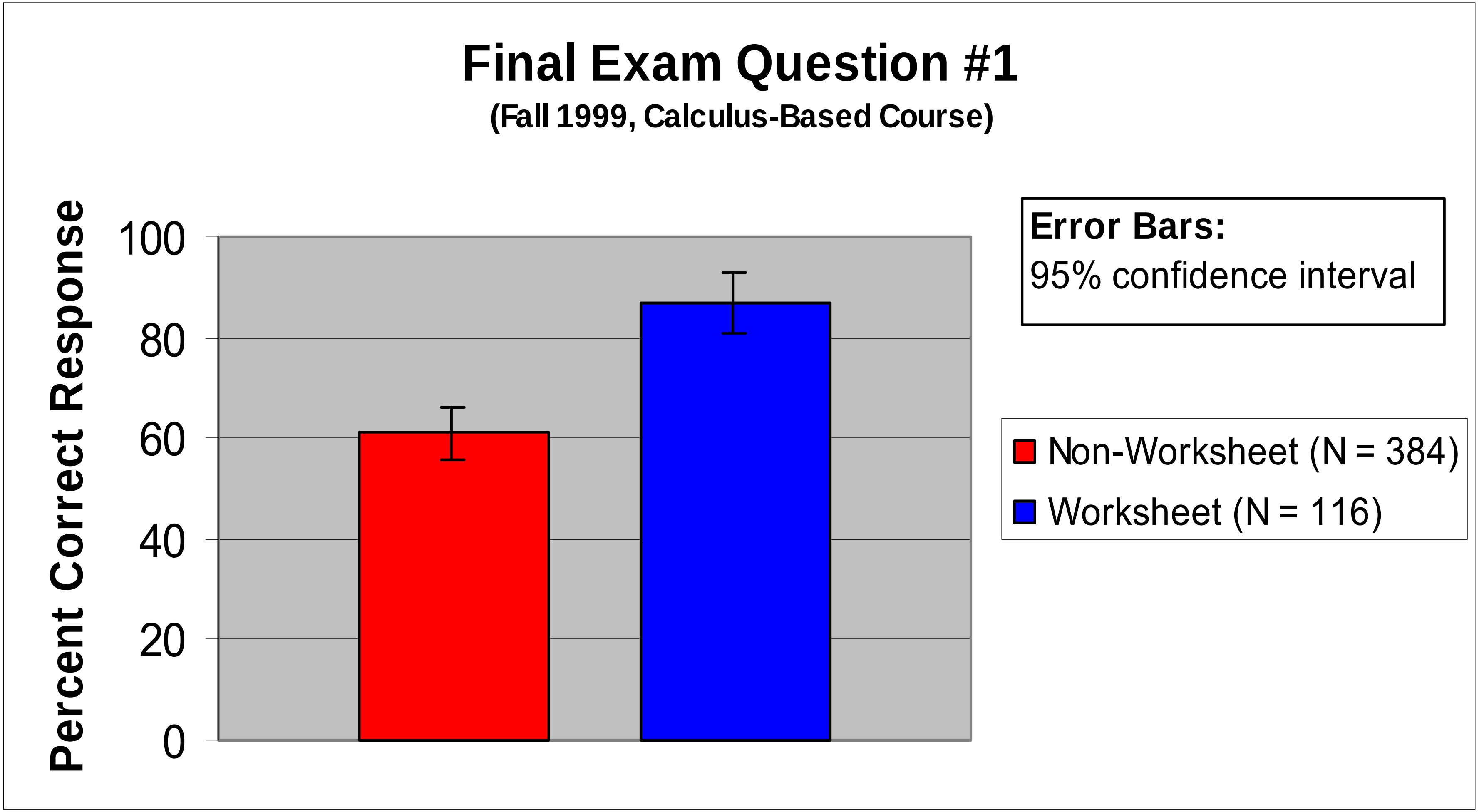
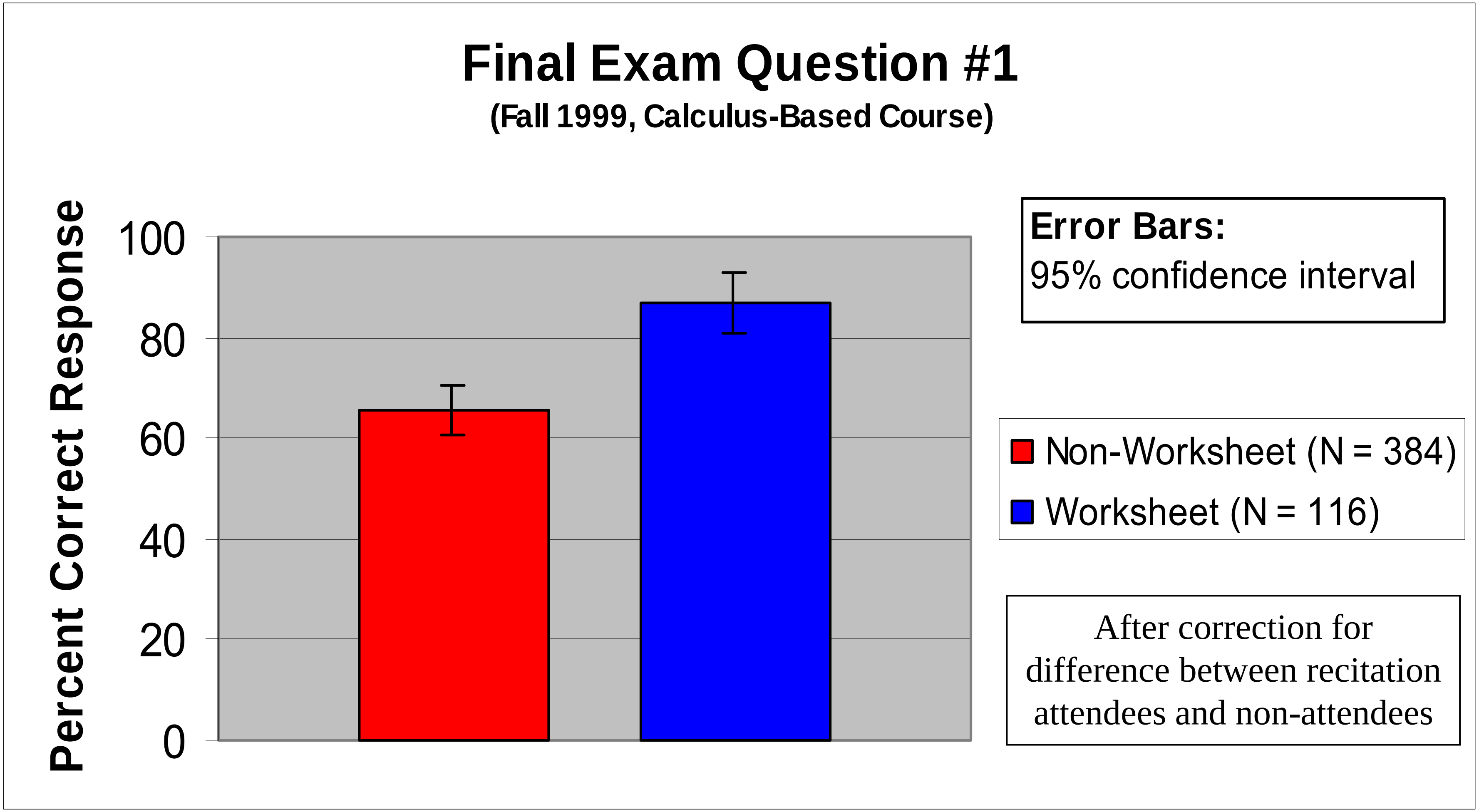

Final Exam Question #1
(Fall 1999, Calculus-Based Course)
Percent Correct Response
100
80
60
40
20
0
Error Bars:
95% confidence interval
Non-Worksheet (N = 384)
Worksheet (N = 116)



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Percent Correct Response
100
80
60
40
20
0
Error Bars:
95% confidence interval
Non-Worksheet (N = 384)
Worksheet (N = 116)
After correction for difference between recitation attendees and non-attendees

Final Exam Question #2

Final Exam Question #2

Two lead spheres of mass *M* are separated by a distance *r*. They are isolated in space with no other masses nearby. The magnitude of the gravitational force experienced by each mass is *F*. Now one of the masses is doubled, and they are pushed farther apart to a separation of 2*r*. Then, the magnitudes of the gravitational forces experienced by the masses are:

A. equal, and are equal to *F.*

B. equal, and are larger than *F.*

C. equal, and are smaller than *F.*

D. not equal, but one of them is larger than *F.*

E. not equal, but neither of them is larger than *F.*

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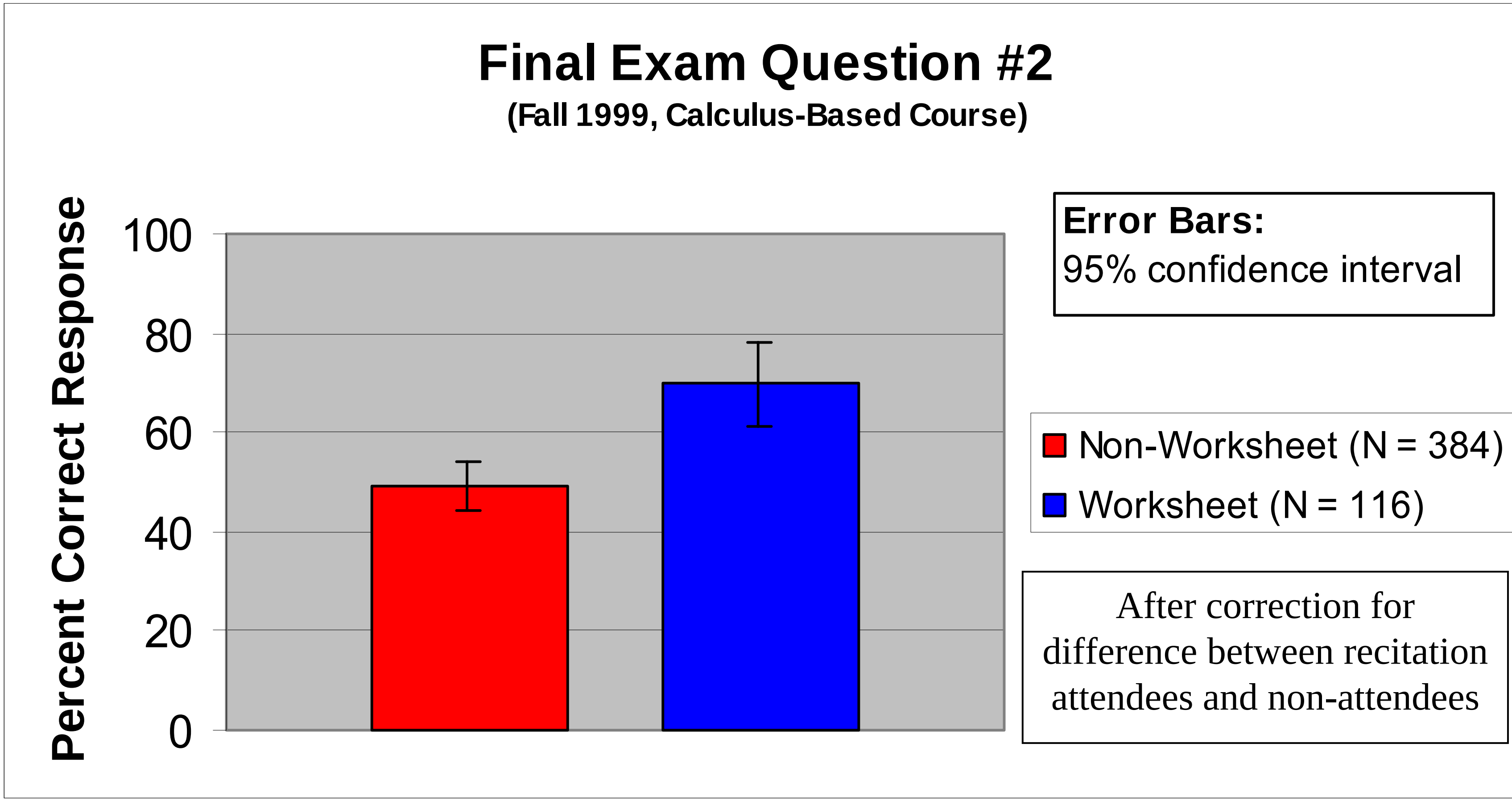
Final Exam Question #2
(Fall 1999, Calculus-Based Course)
Percent Correct Response
100
80
60
40
20
0
Error Bars:
95% confidence interval
Non-Worksheet (N = 384)
Worksheet (N = 116)
After correction for difference between recitation attendees and non-attendees

Outline

Physics Education as a Research Problem

- Goals and methods of PER
- Some specific issues

Research-Based Instructional Methods

- Principles of research-based instruction
- Instruction in large classes

Research-Based Curriculum Development

- A “model” problem: law of gravitation
- Student reasoning in thermodynamics

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- Student reasoning in thermodynamics

Research on the Teaching and Learning of Thermal Physics

- Investigate student learning of classical and 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

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*).

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

Upper-level Thermal Physics Course

- **Topics:** classical macroscopic thermodynamics; statistical thermodynamics

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

Performance Comparison: Upper-level vs. Introductory Students

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

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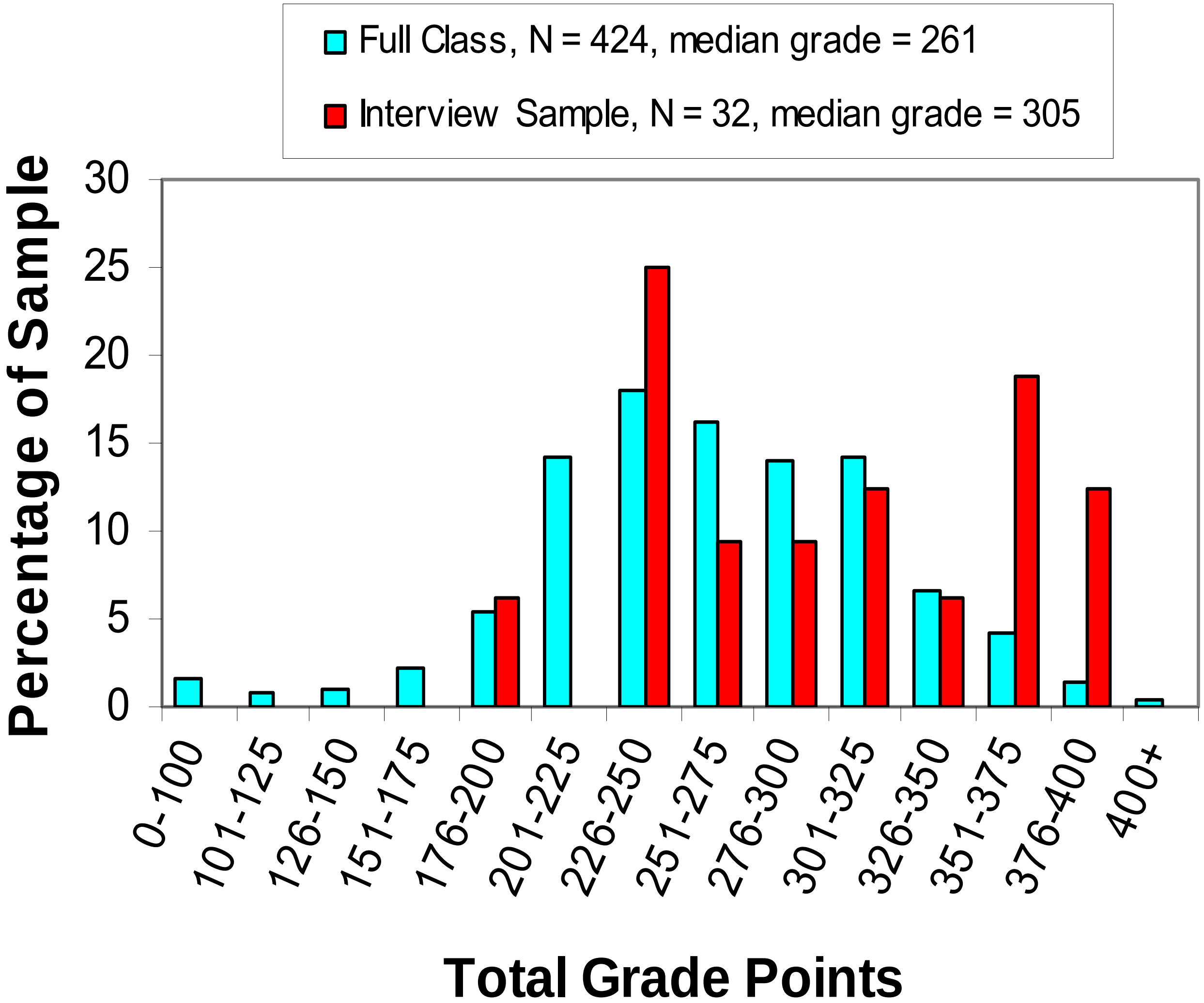
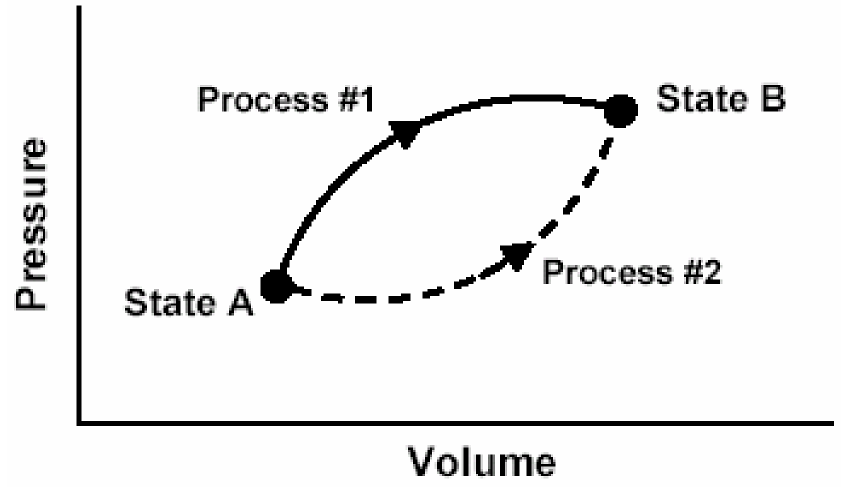
Grade Distributions: Interview Sample vs. Full Class



***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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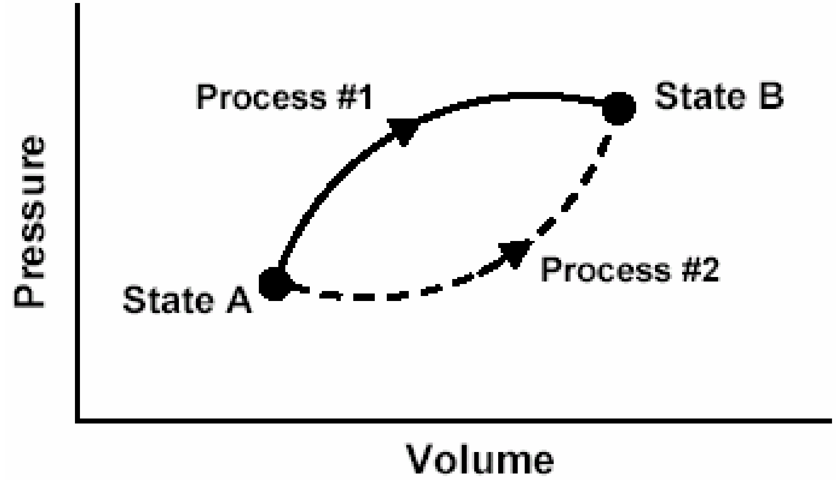

[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

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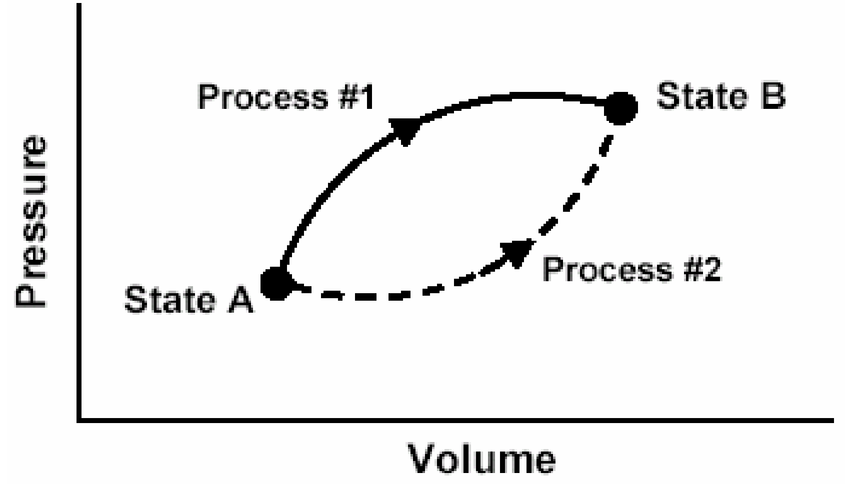

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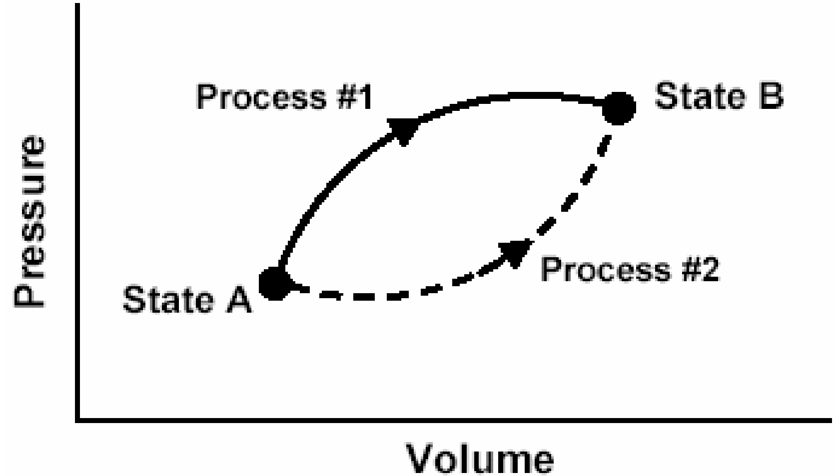
$$W = \int_{V_A}^{V_B} P\,dV$$



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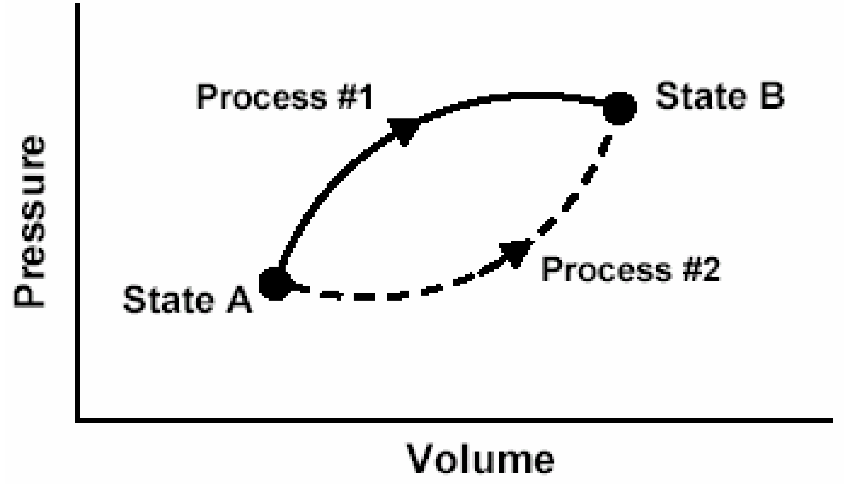

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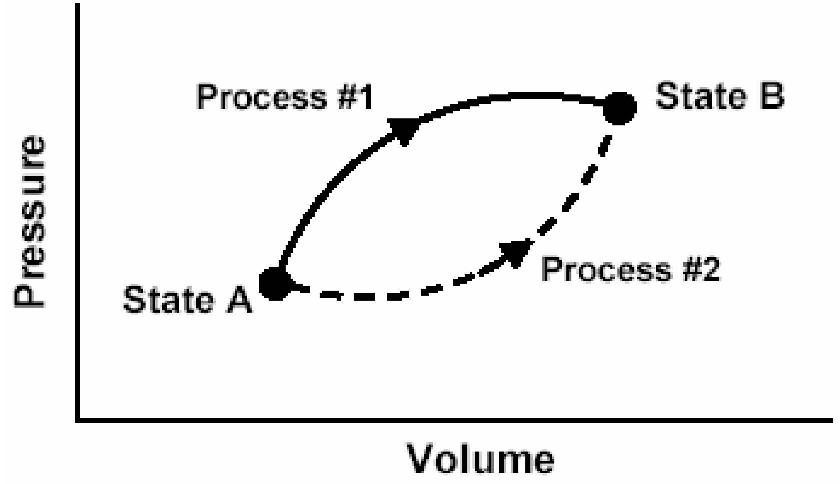

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Responses to Diagnostic Question #1
(Work question)

	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)	**2002** Introductory Physics (Post-test) Interview Sample (*N*=32)	**2003** Thermal Physics (Pretest) (*N*=14)
$W_1 = W_2$	**30%**	**22%**	**20%**

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

About one-quarter of all students believe work done is equal in both processes

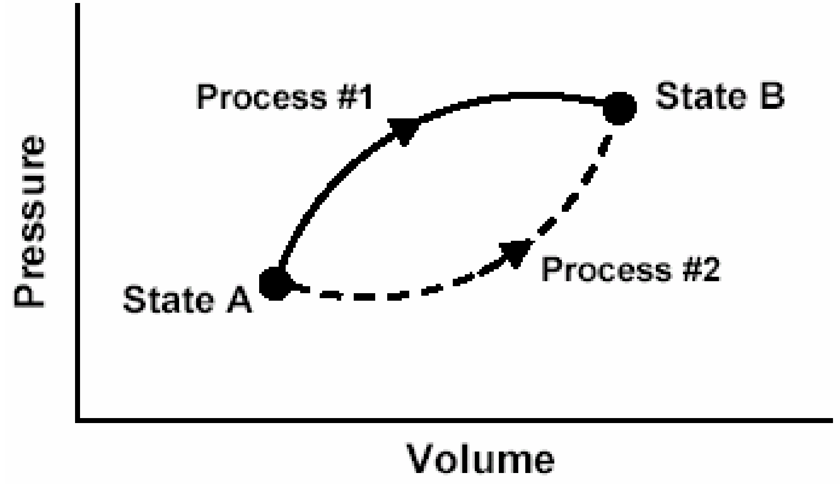
Explanations Given by Thermal Physics Students to Justify $W_1 = W_2$

- "*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

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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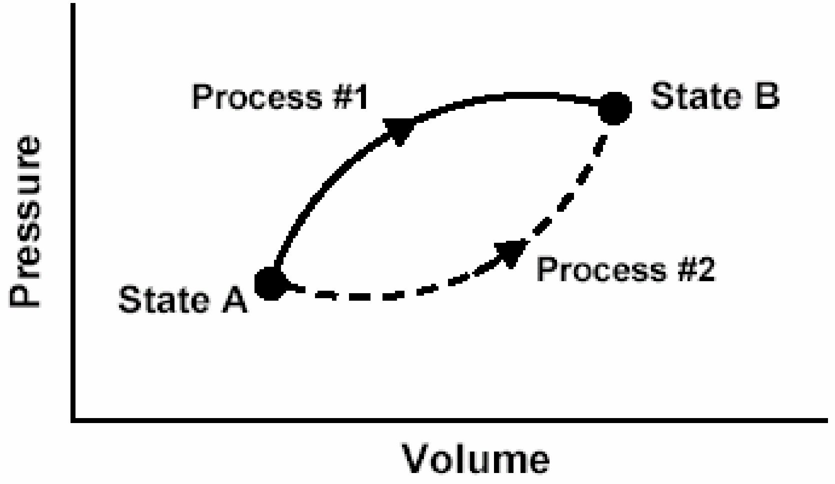

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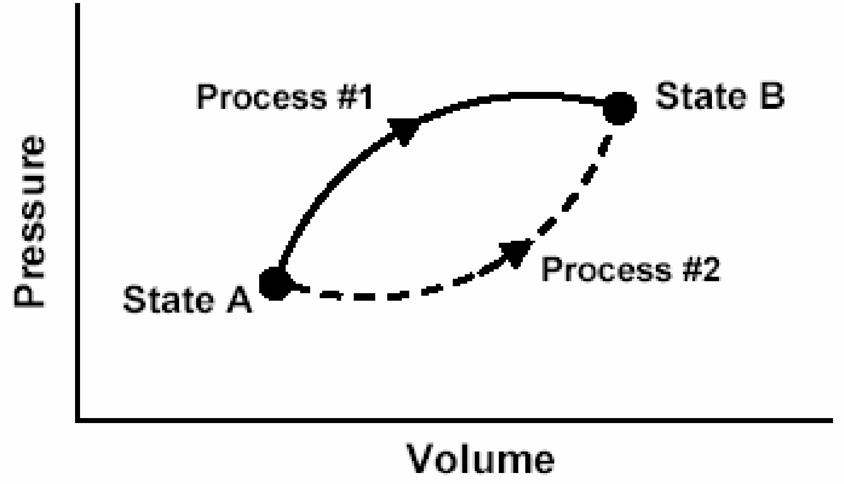
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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



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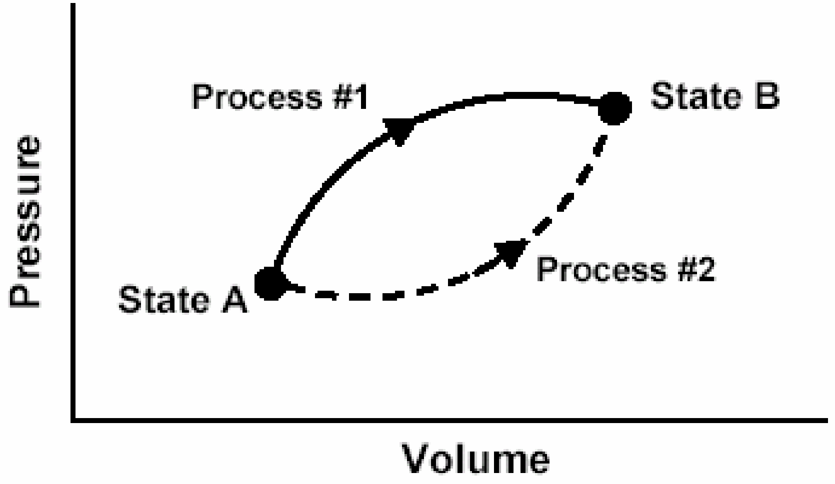
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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)	**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)**
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Responses to Diagnostic Question #2
(Heat question)

$Q_1 > Q_2$			
[Correct answer]			

Responses to Diagnostic Question #2
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$Q_1 > Q_2$	45%	34%	35%

Responses to Diagnostic Question #2

(Heat question)

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

Responses to Diagnostic Question #2
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Correct or partially correct explanation	**11%**	**19%**	**30%**

Performance of upper-level students better than that of most introductory students, but still weak

Primary Findings, Introductory Course

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

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Cyclic Process Questions

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

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

Cyclic Process Questions

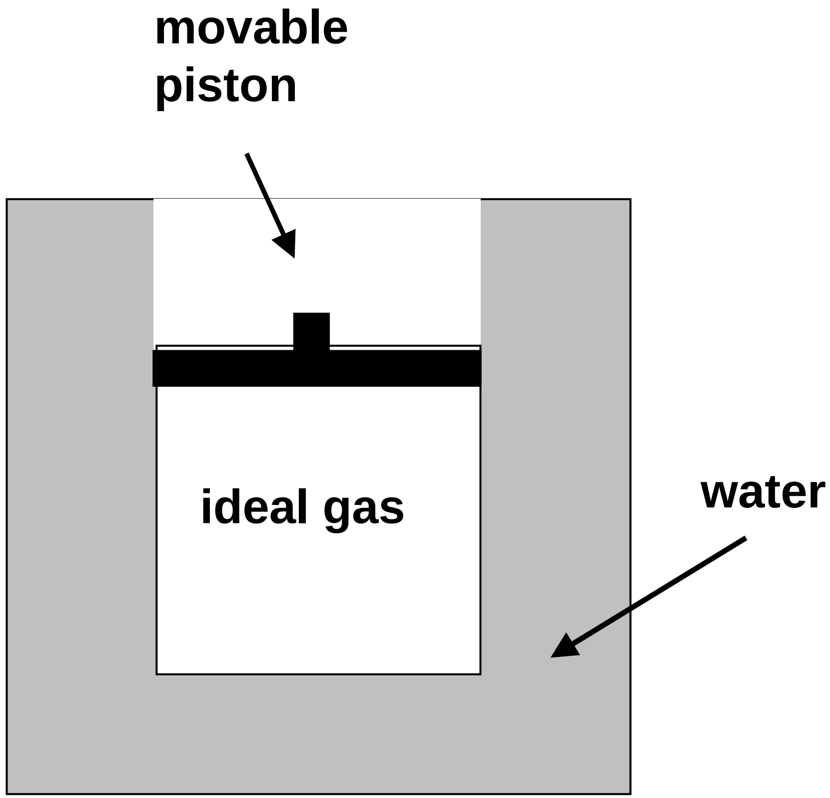
A fixed quantity of ideal gas is contained within a metal cylinder that is sealed with a movable, frictionless, insulating piston.

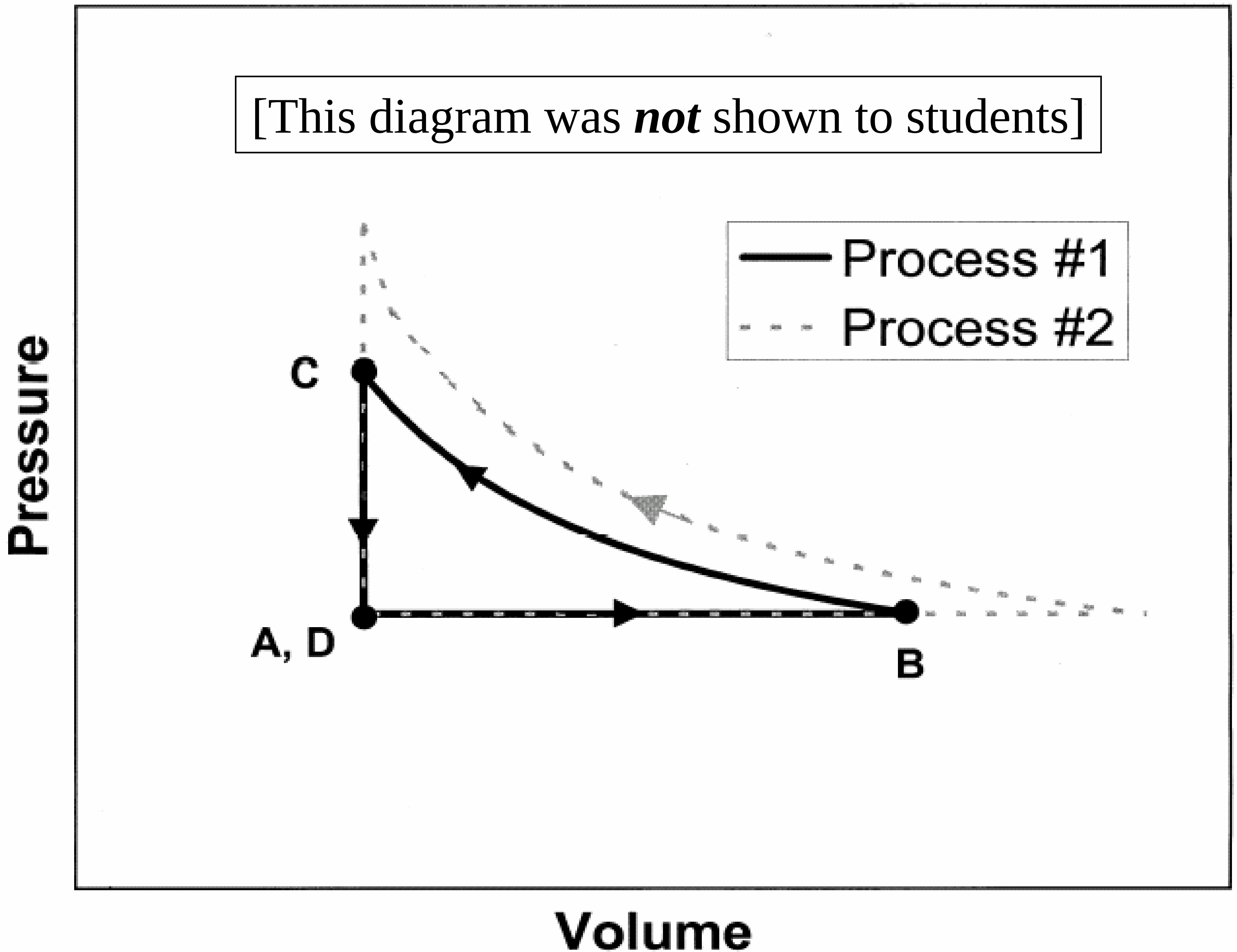
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

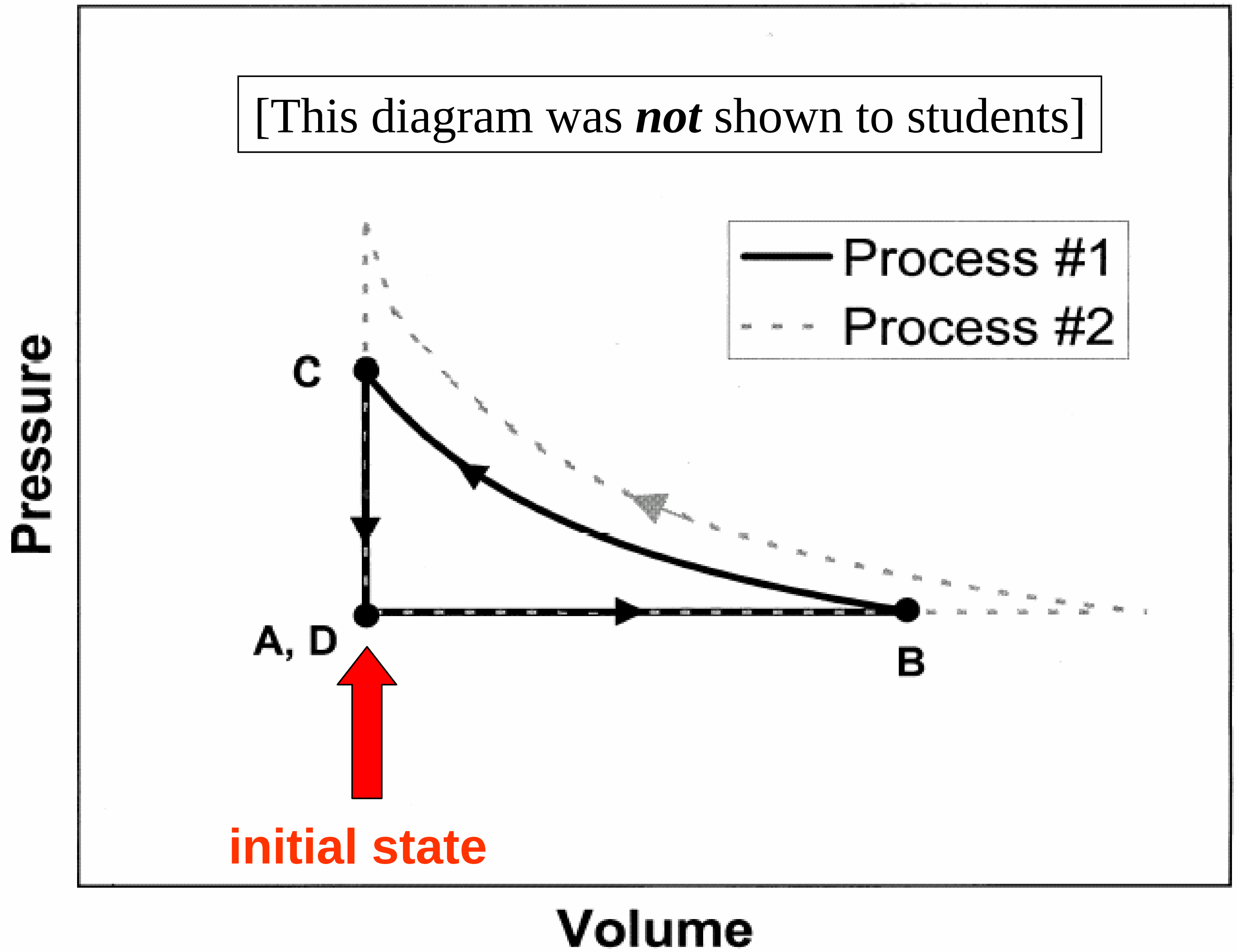
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature

Time *A*

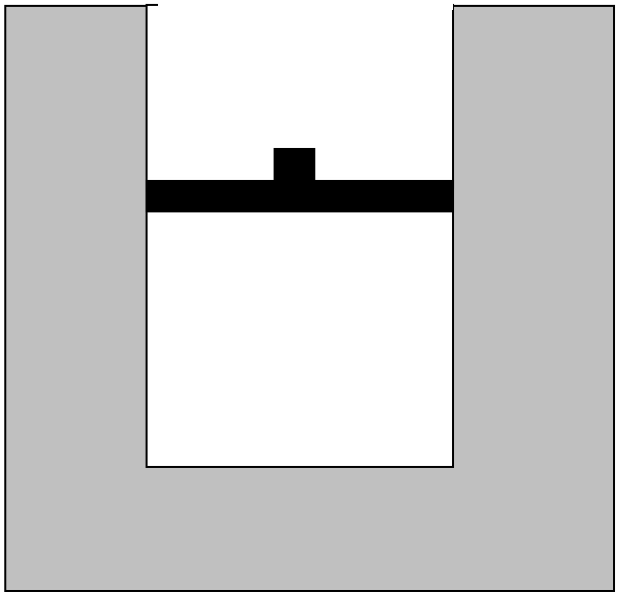
Entire system at room temperature.

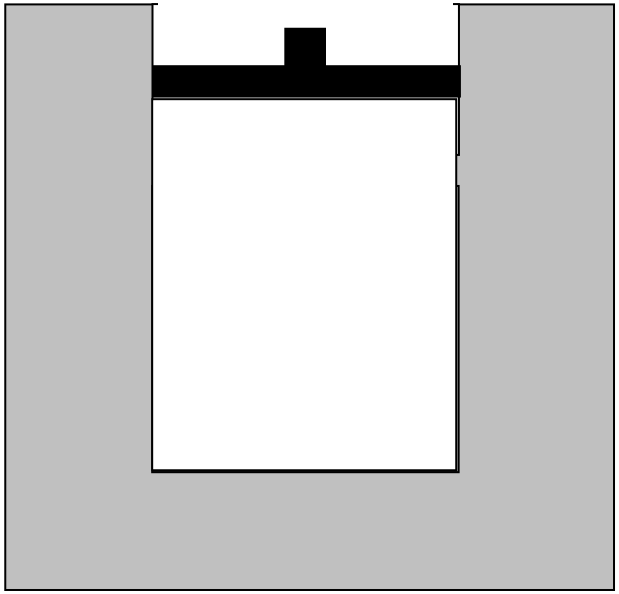



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

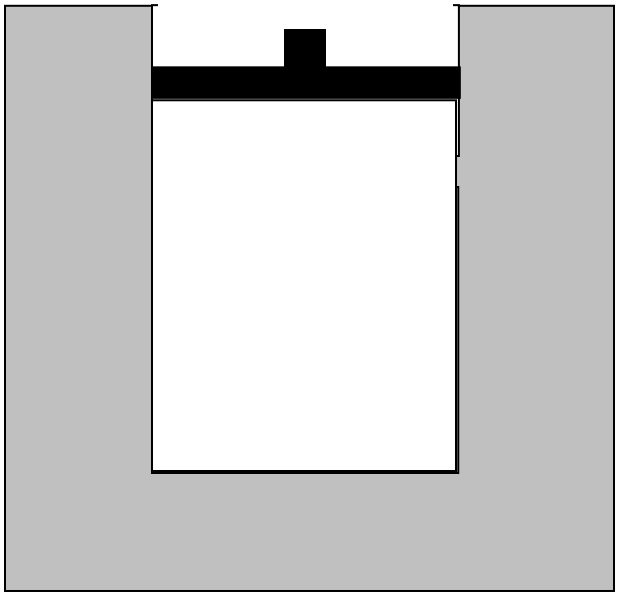

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
initial state
Pressure
Volume

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



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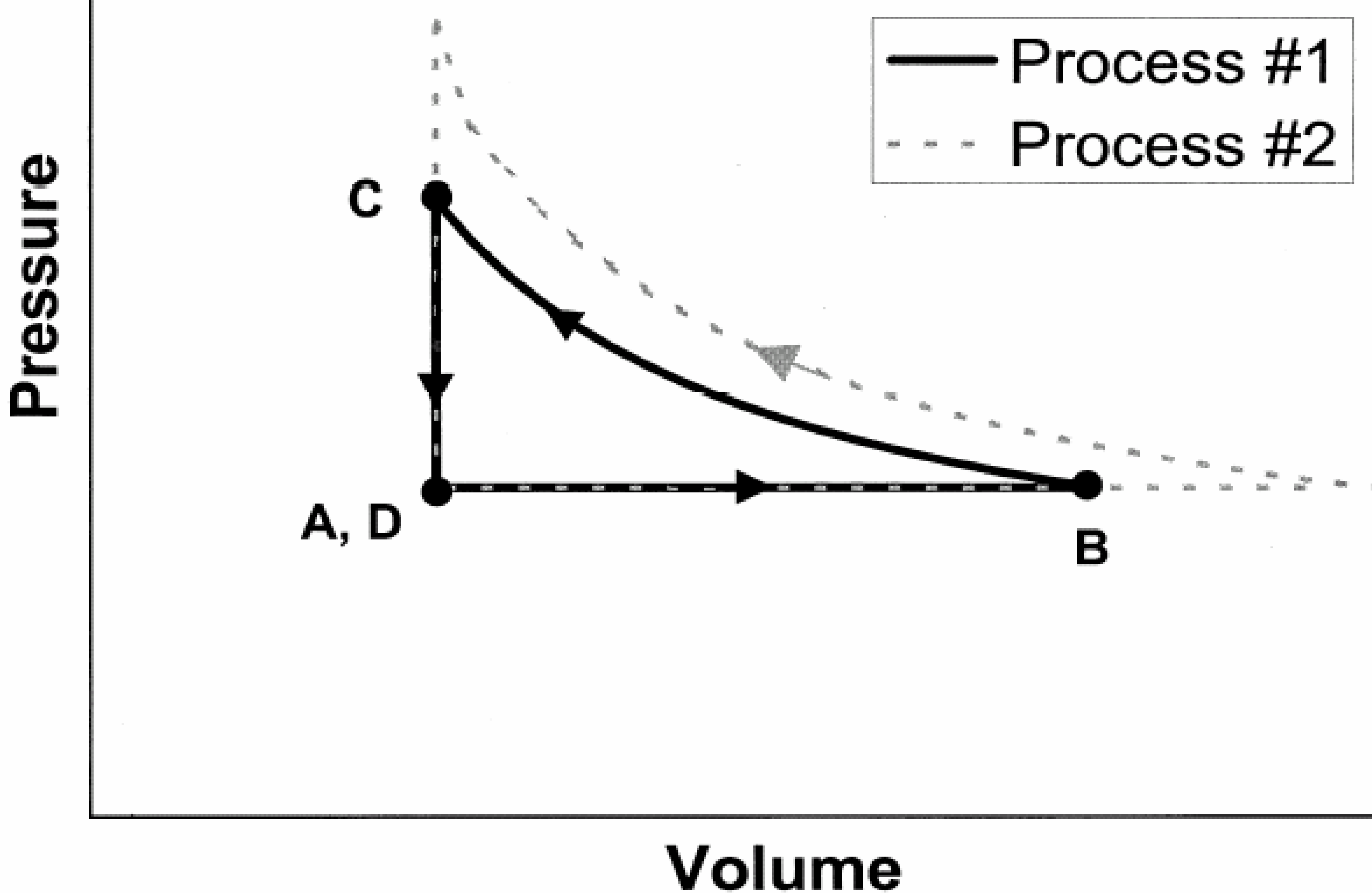

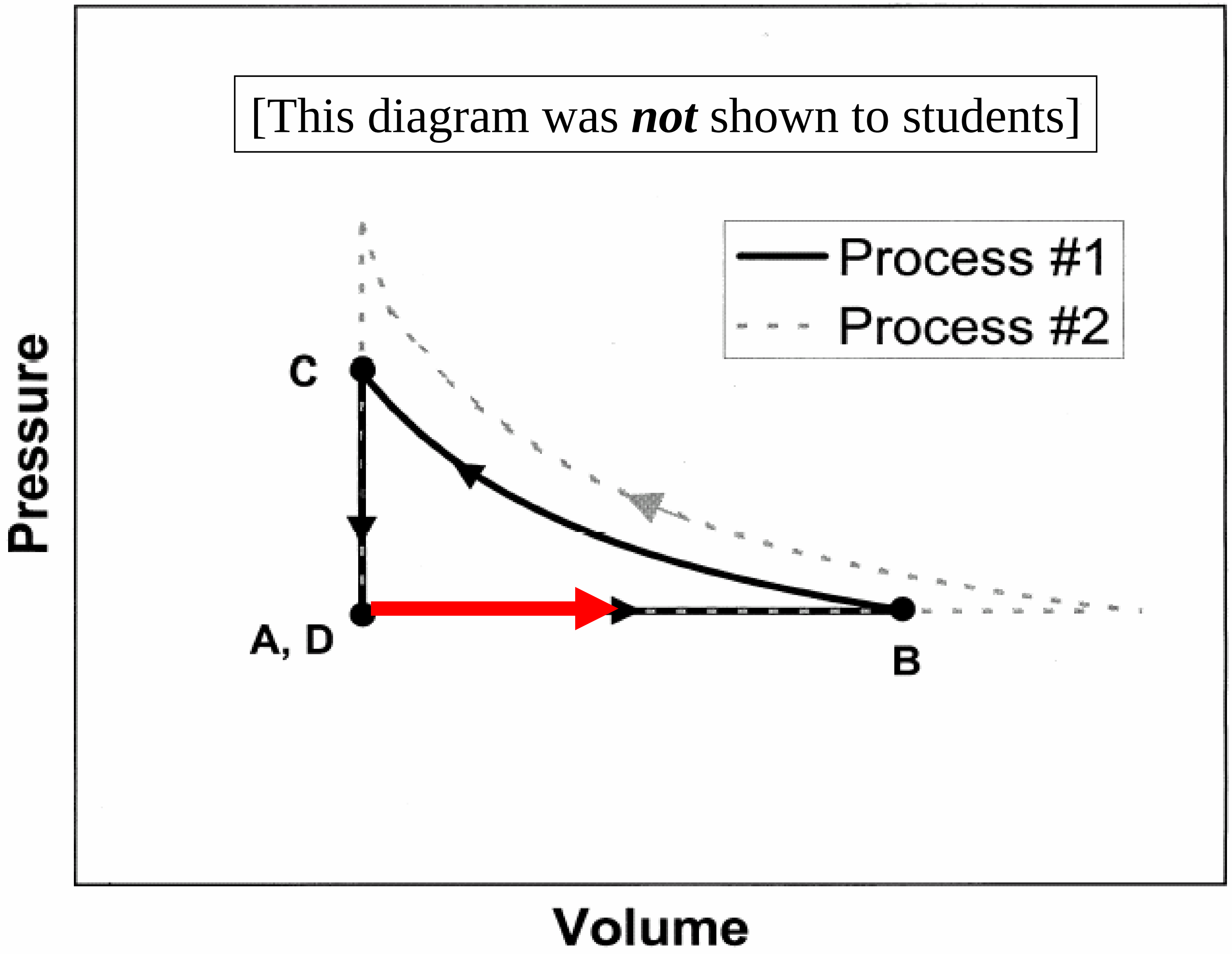

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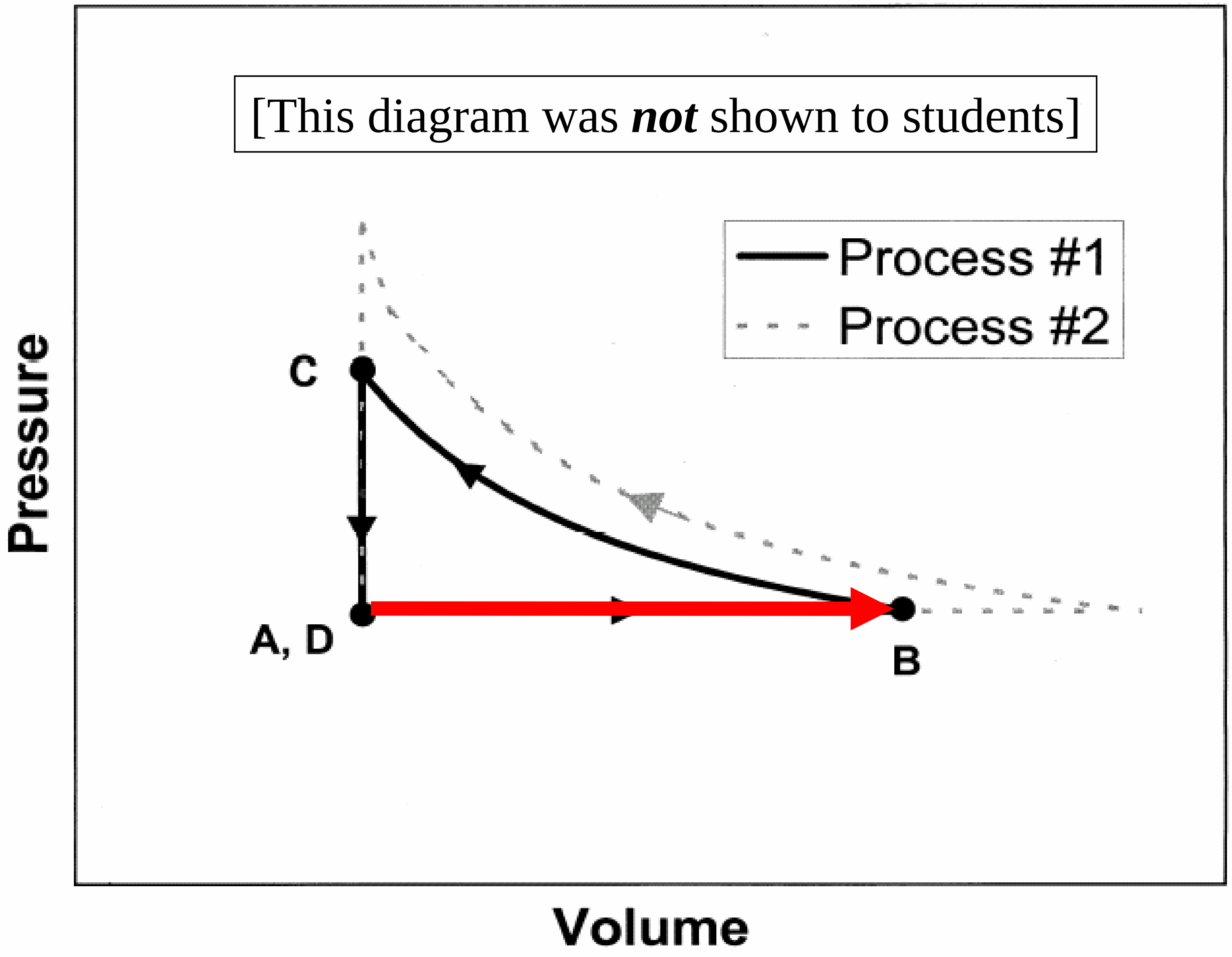
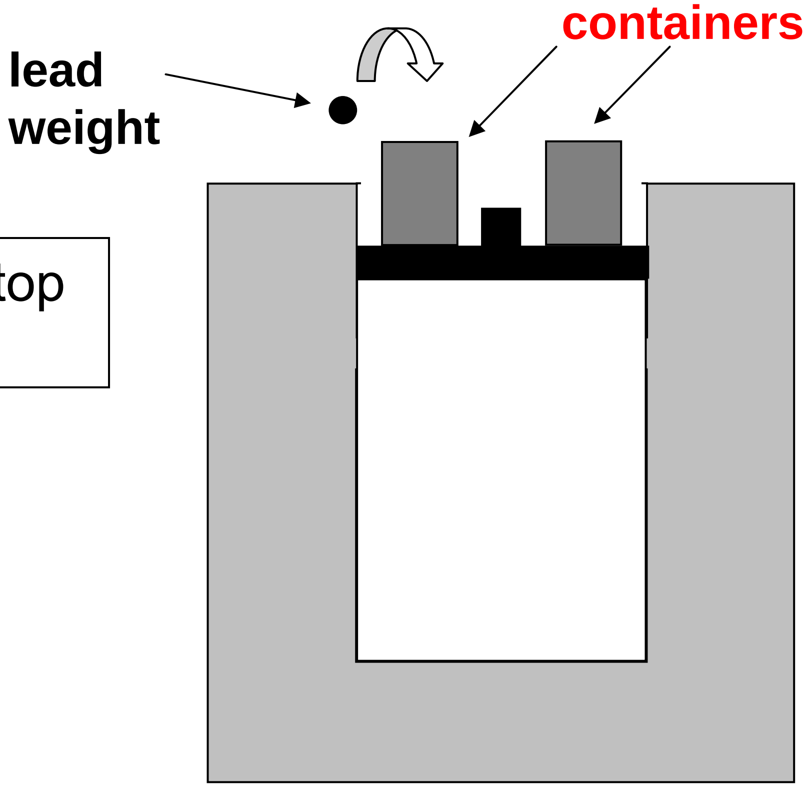
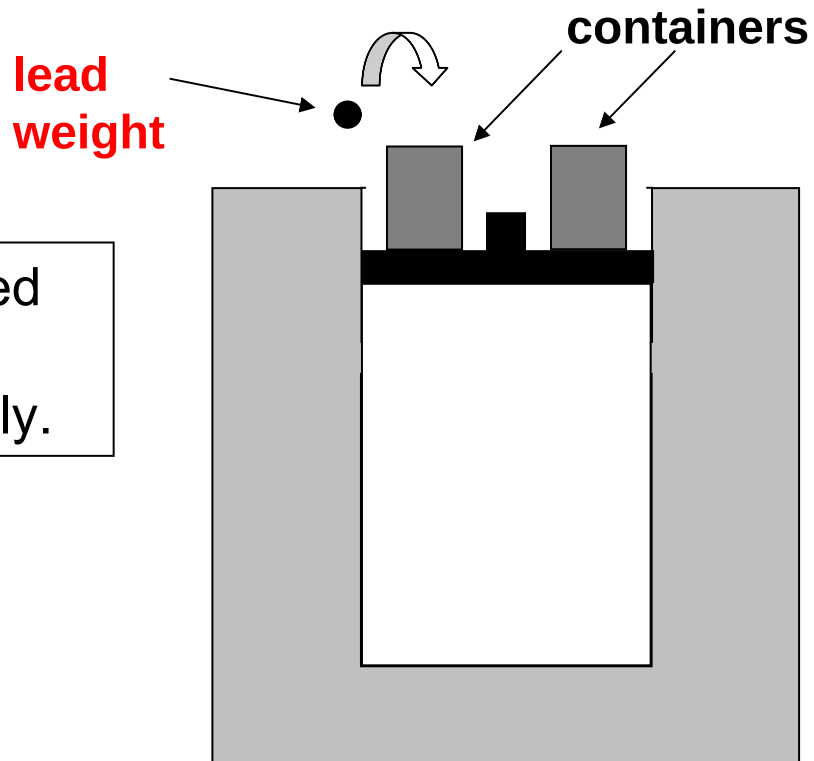
Process #1
Process #2
C
A, D
B
Pressure
Volume

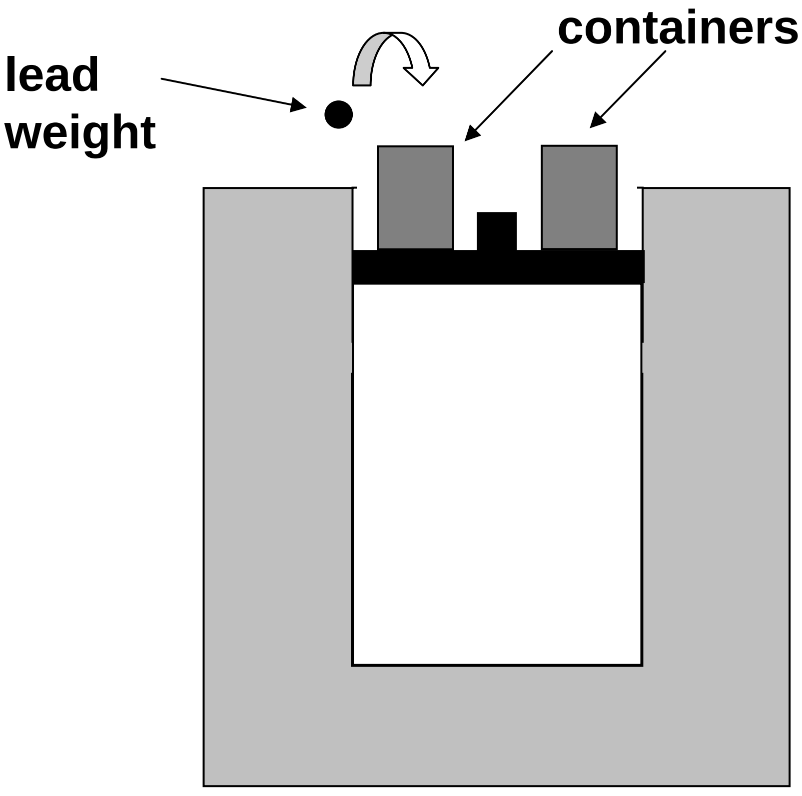

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

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

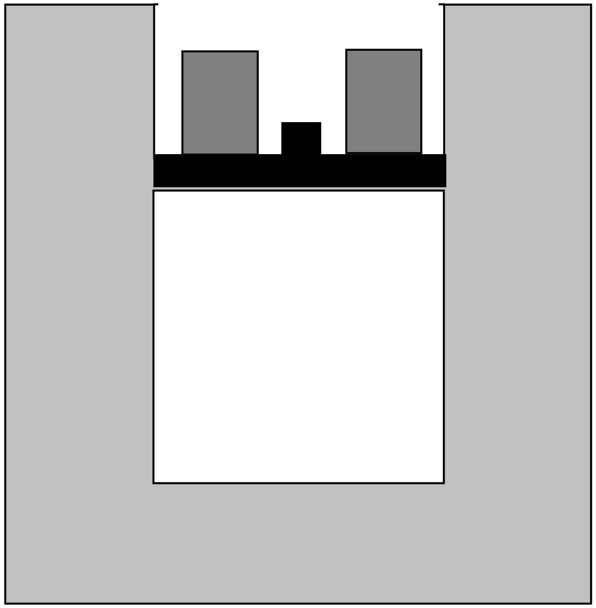


Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly.

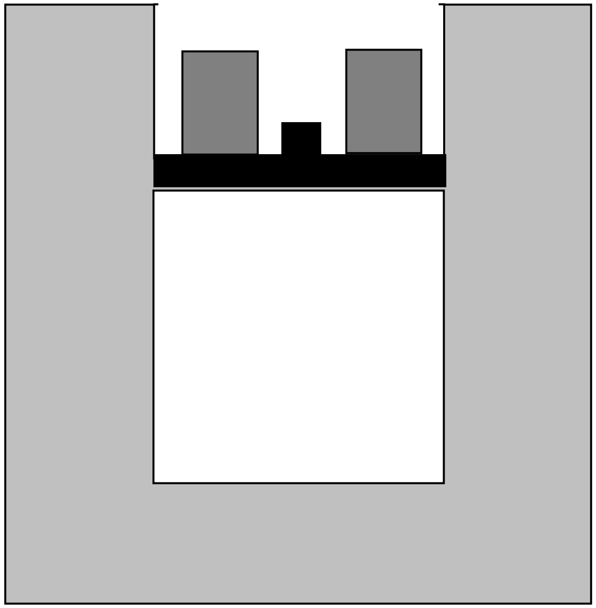




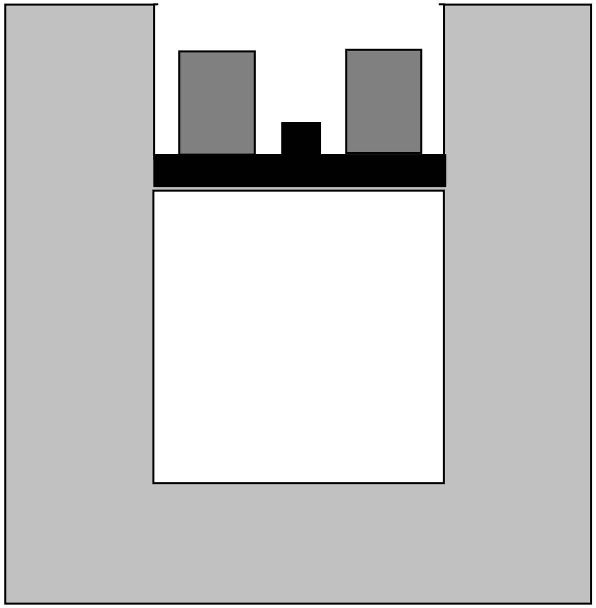
lead
weight
containers



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



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



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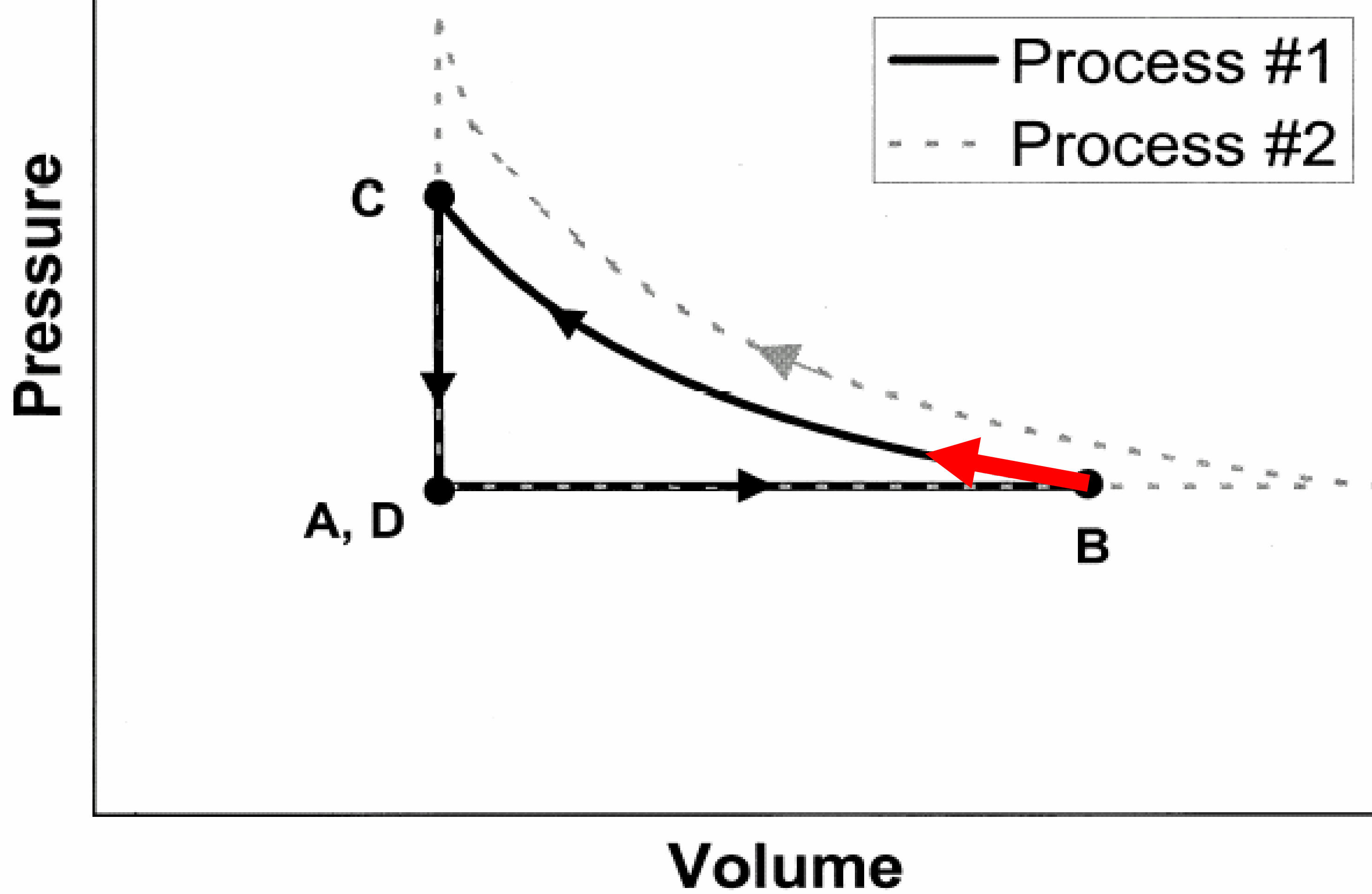

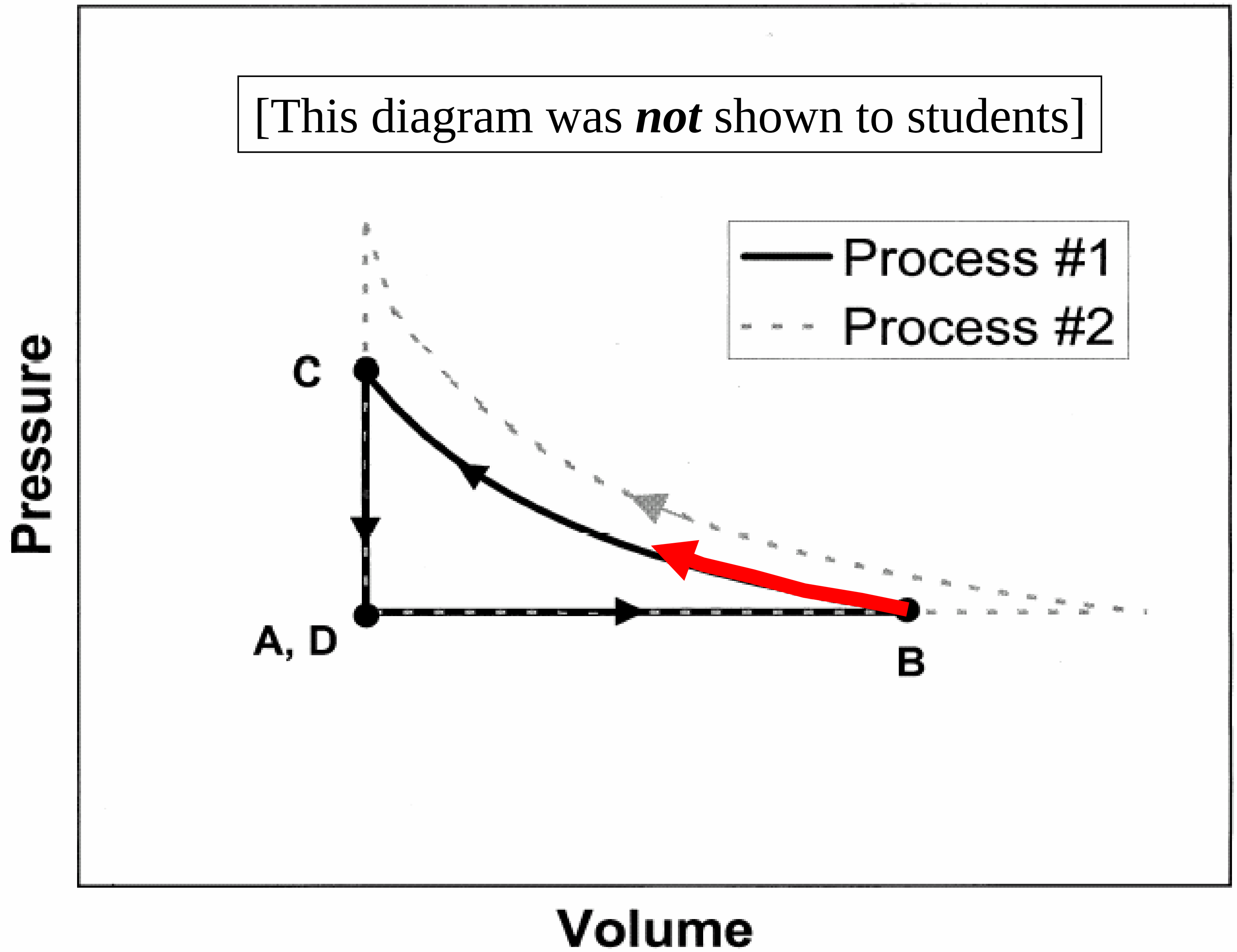

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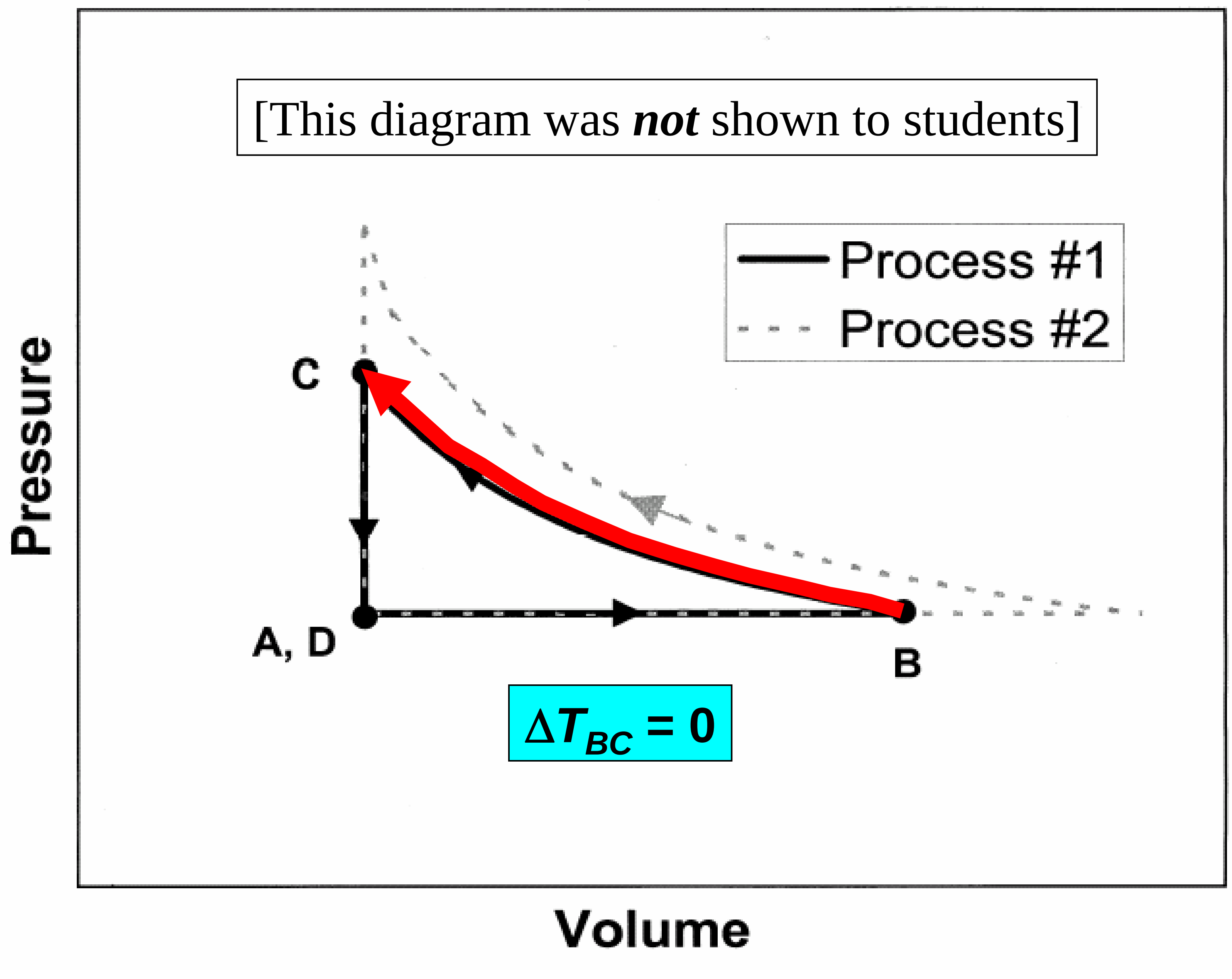
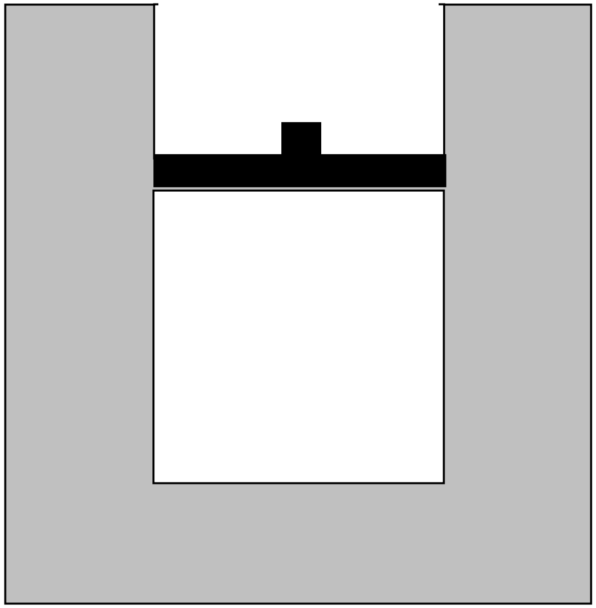
Process #1
Process #2
C
A, D
B
Pressure
Volume

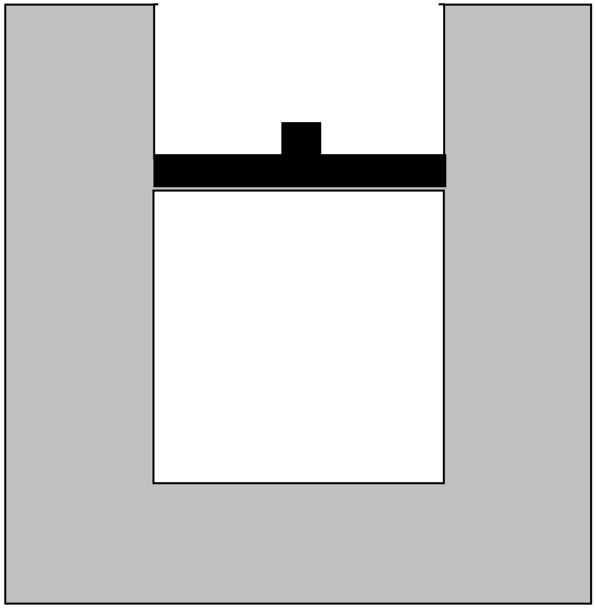


[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
ΔT_BC = 0
Pressure
Volume

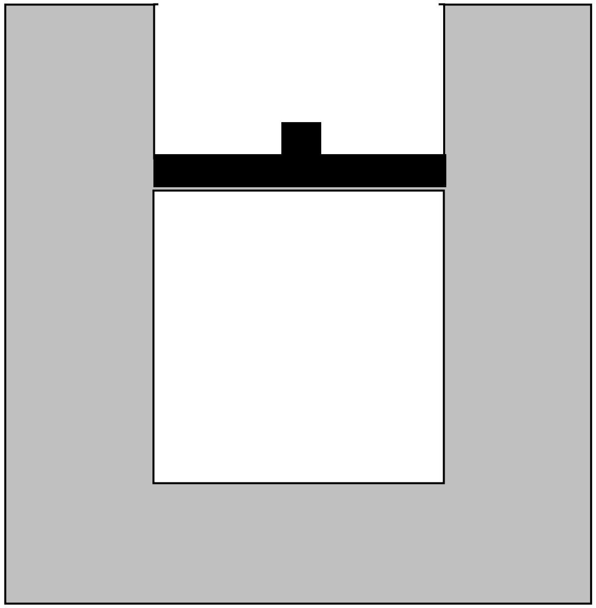
Now, the piston is locked into place so it *cannot move*, and the weights are removed from the piston.



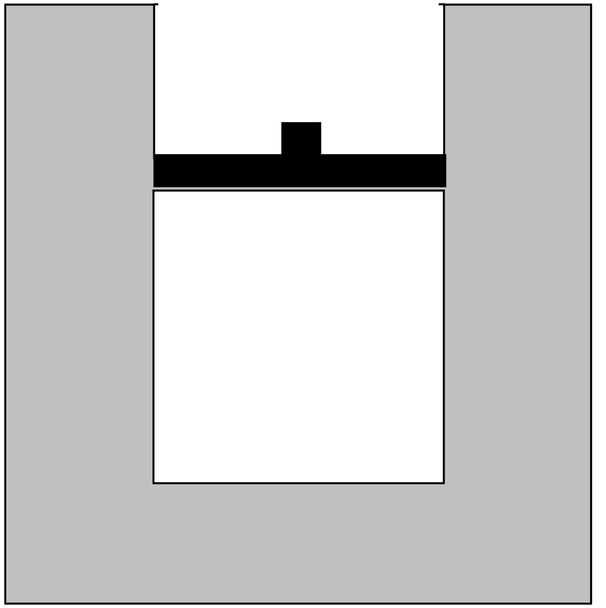
The system is left to sit in the room for many hours.

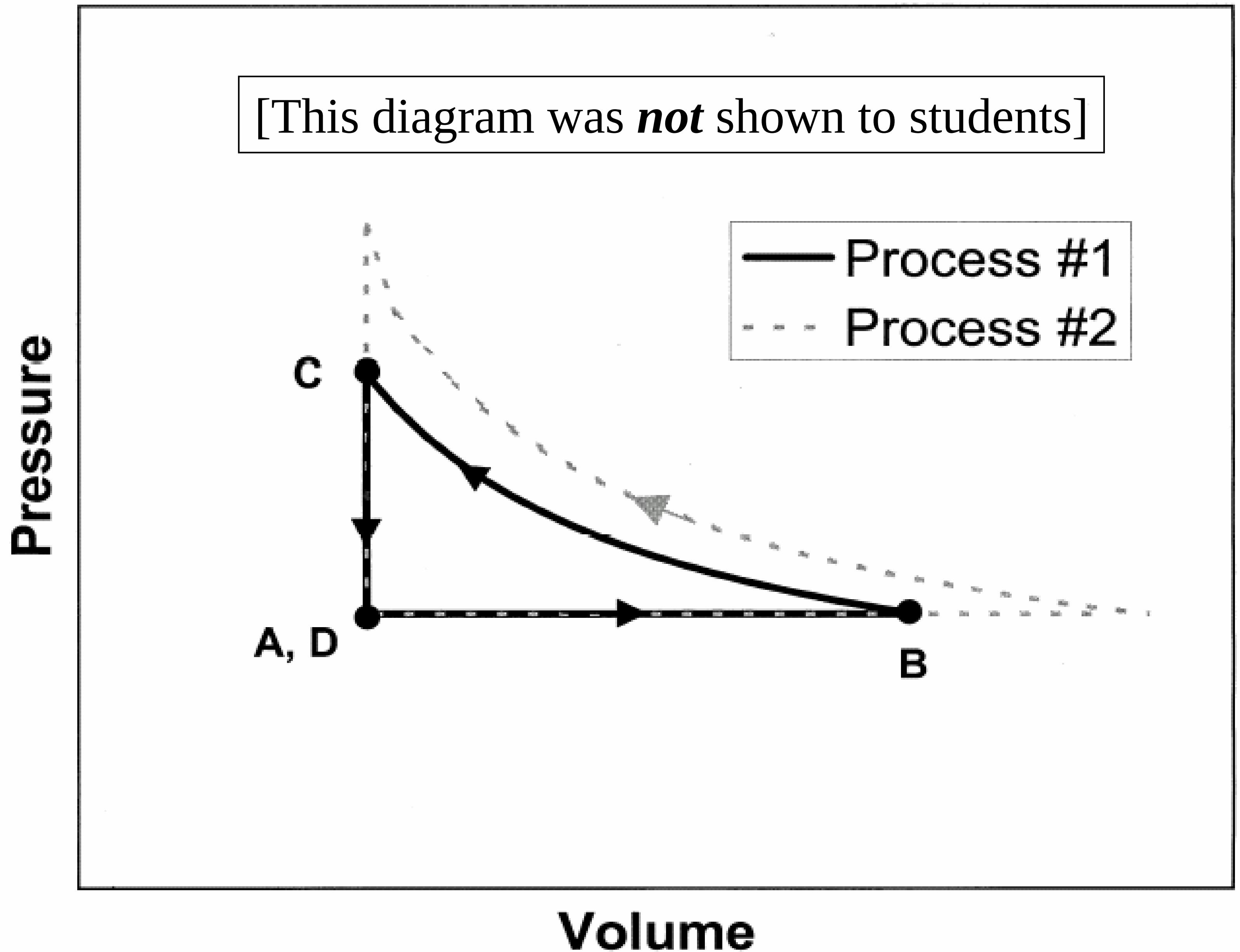


Eventually the entire system cools back down to the same room temperature it had at time ***A*.**



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





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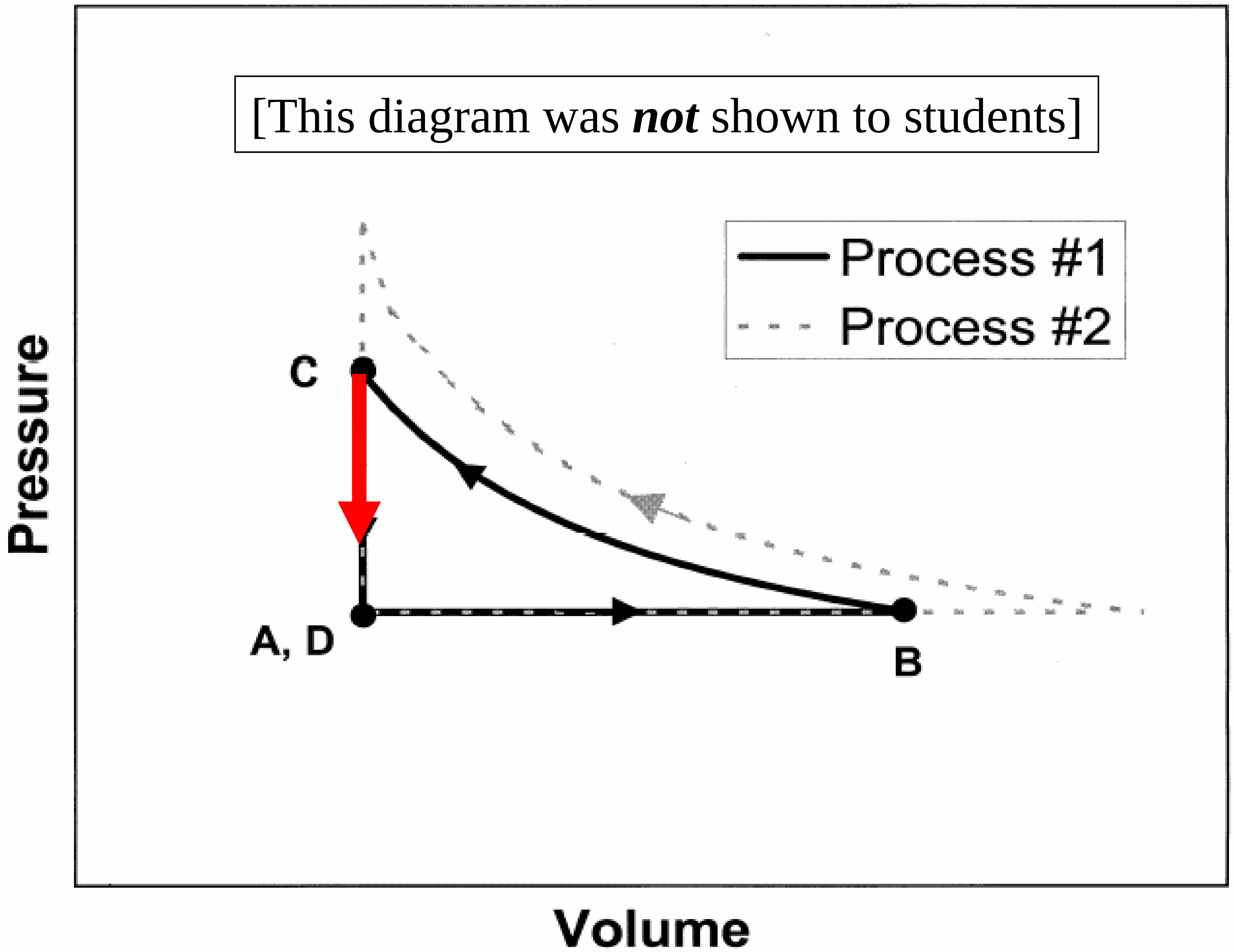
Process #2
C
A, D
B
Pressure
Volume



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Process #2
C
A, D
B
Pressure
Volume

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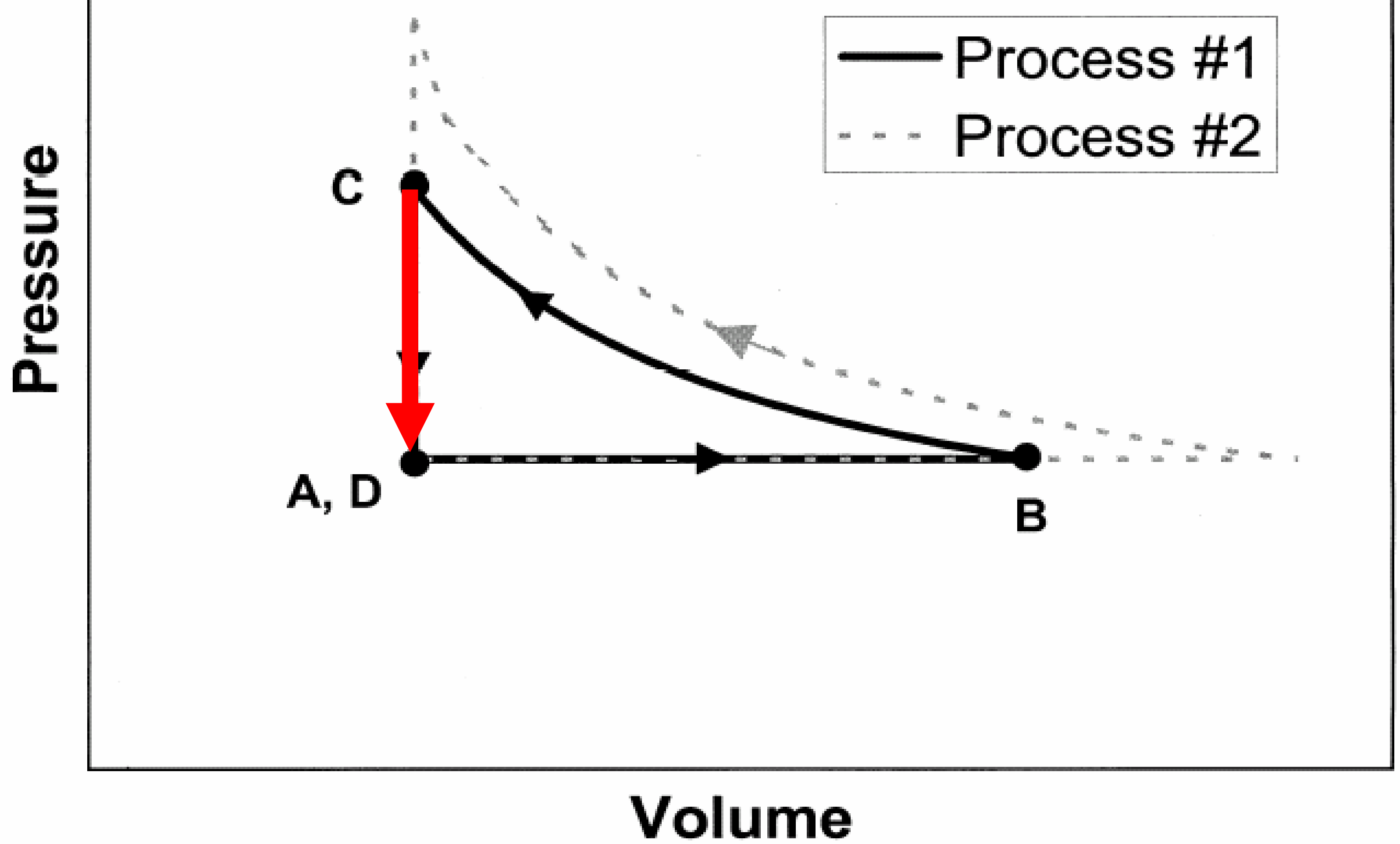

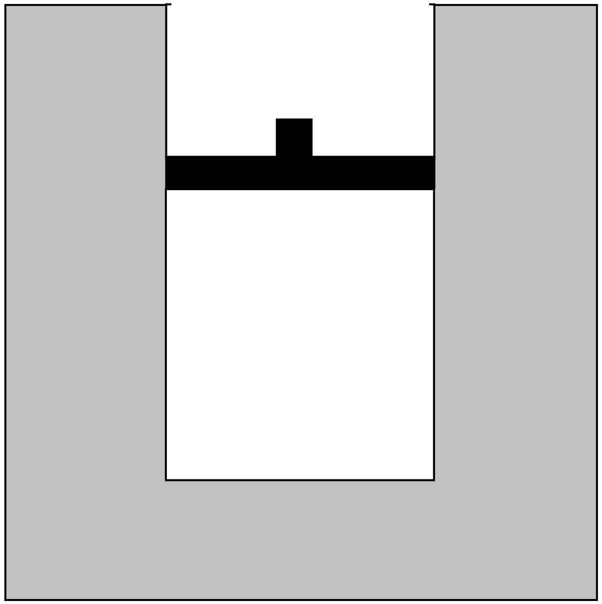

Question #6: Consider ***the entire process*** from time *A* to time *D*.

(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?

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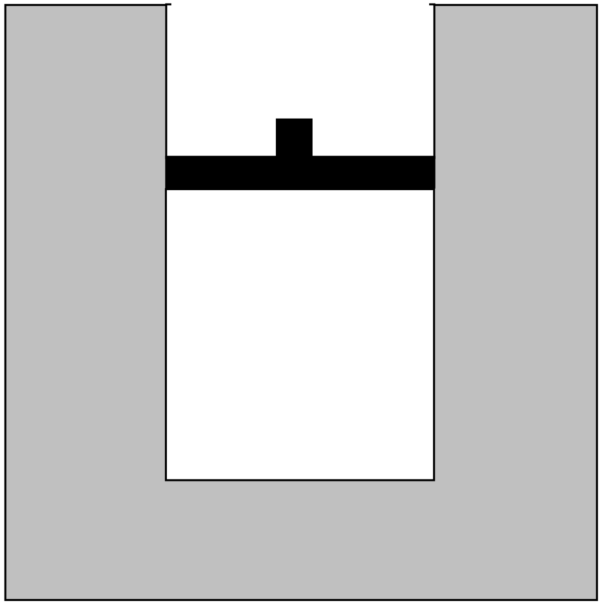

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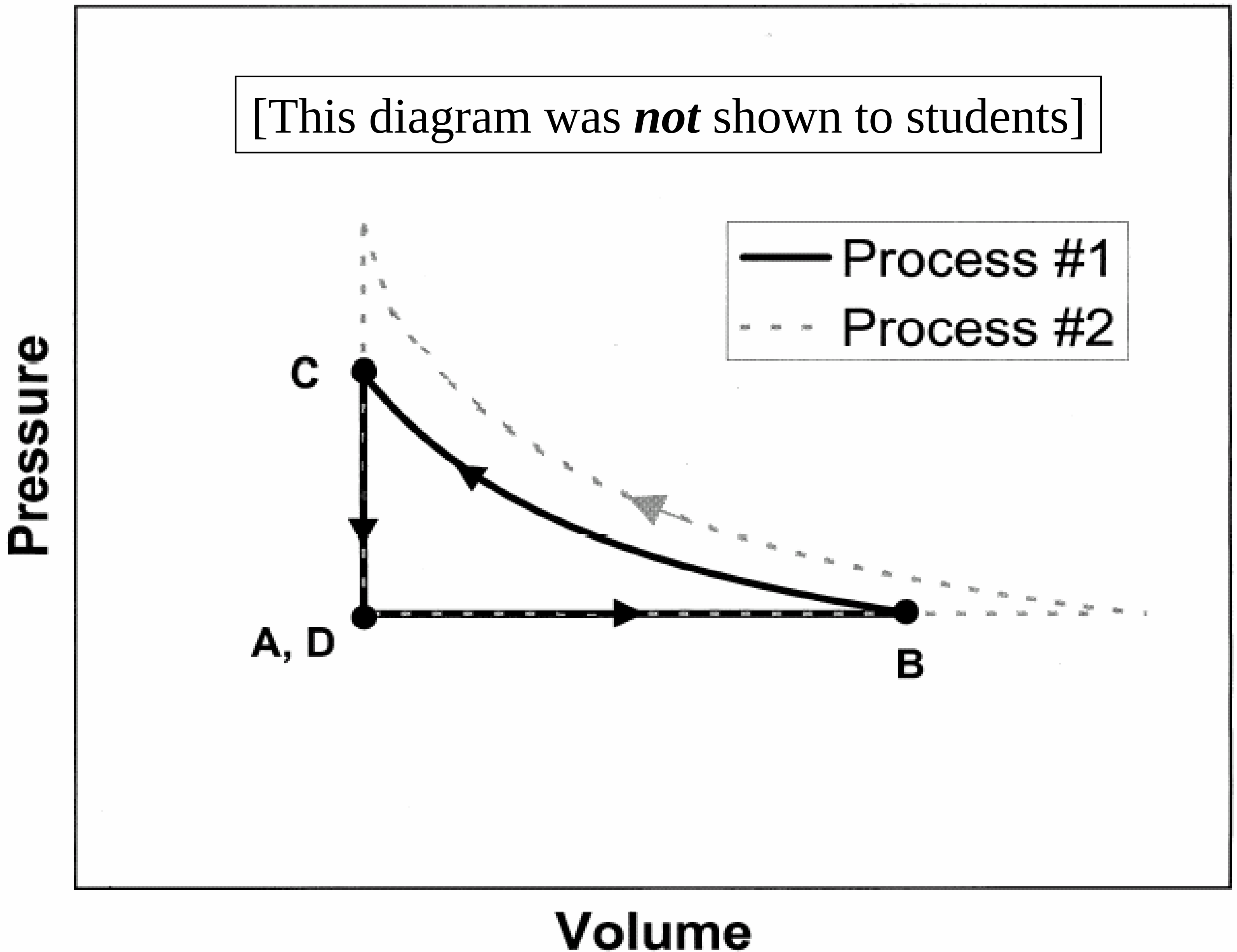
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Process #1
Process #2
C
A, D
B
Pressure
Volume

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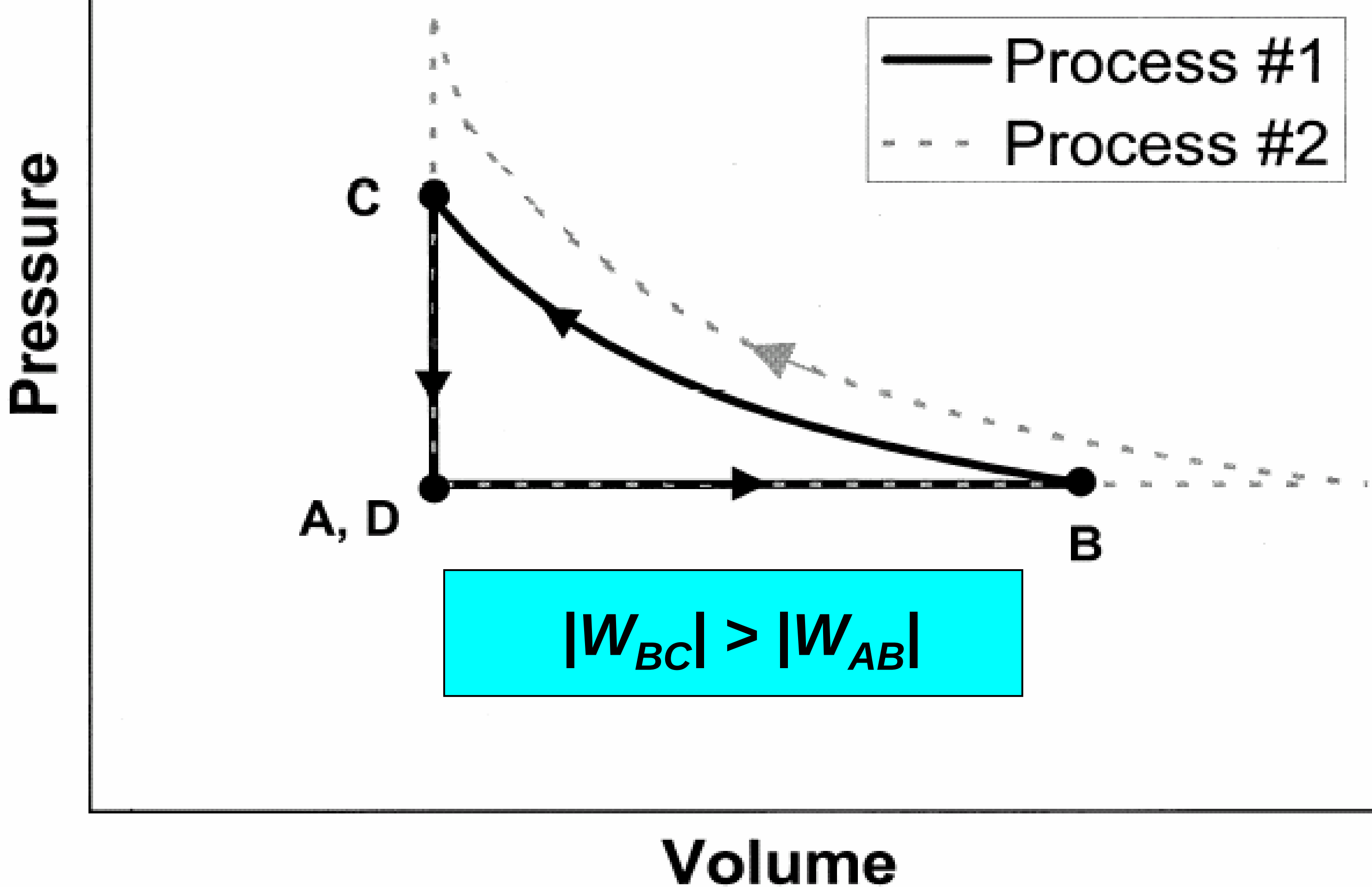
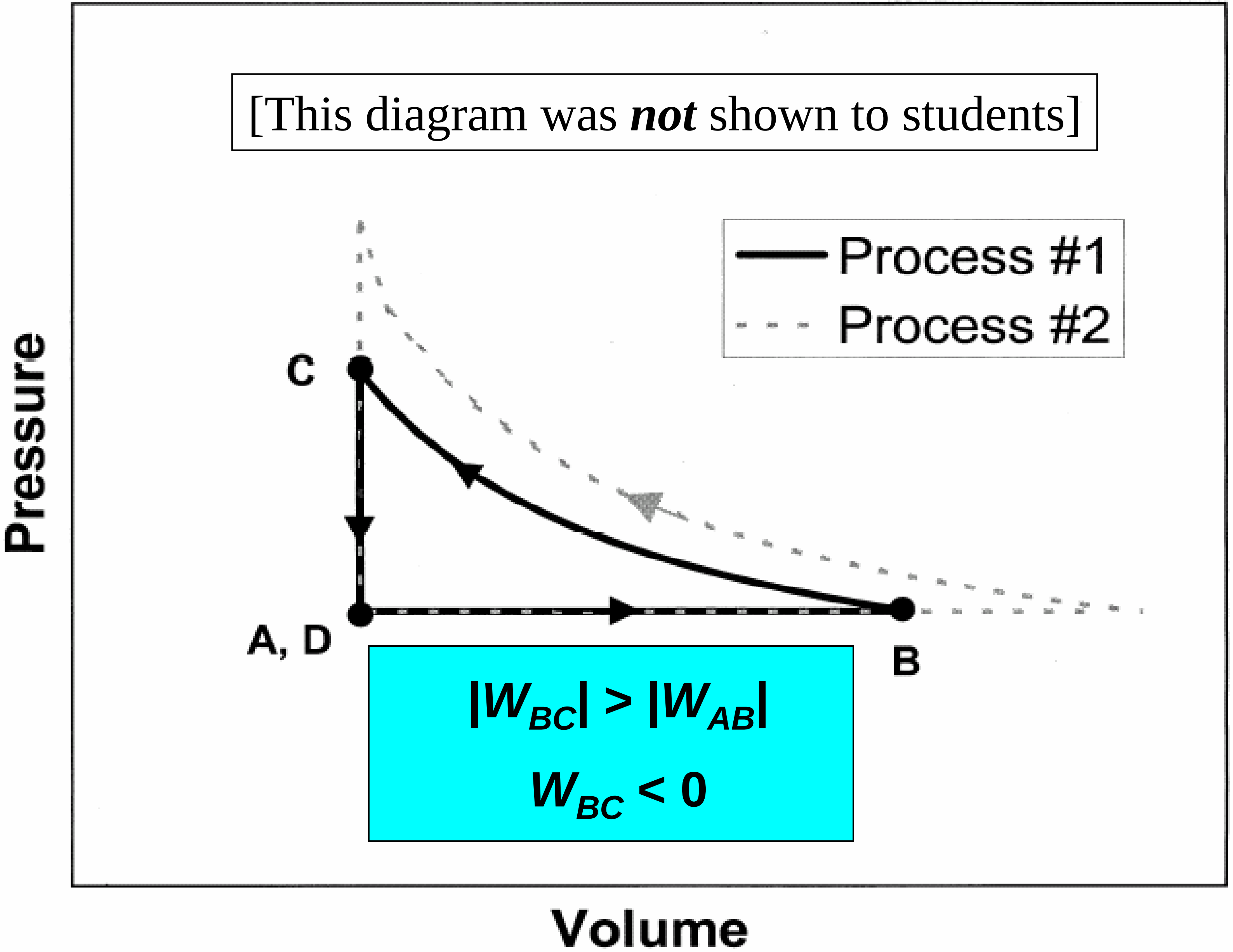


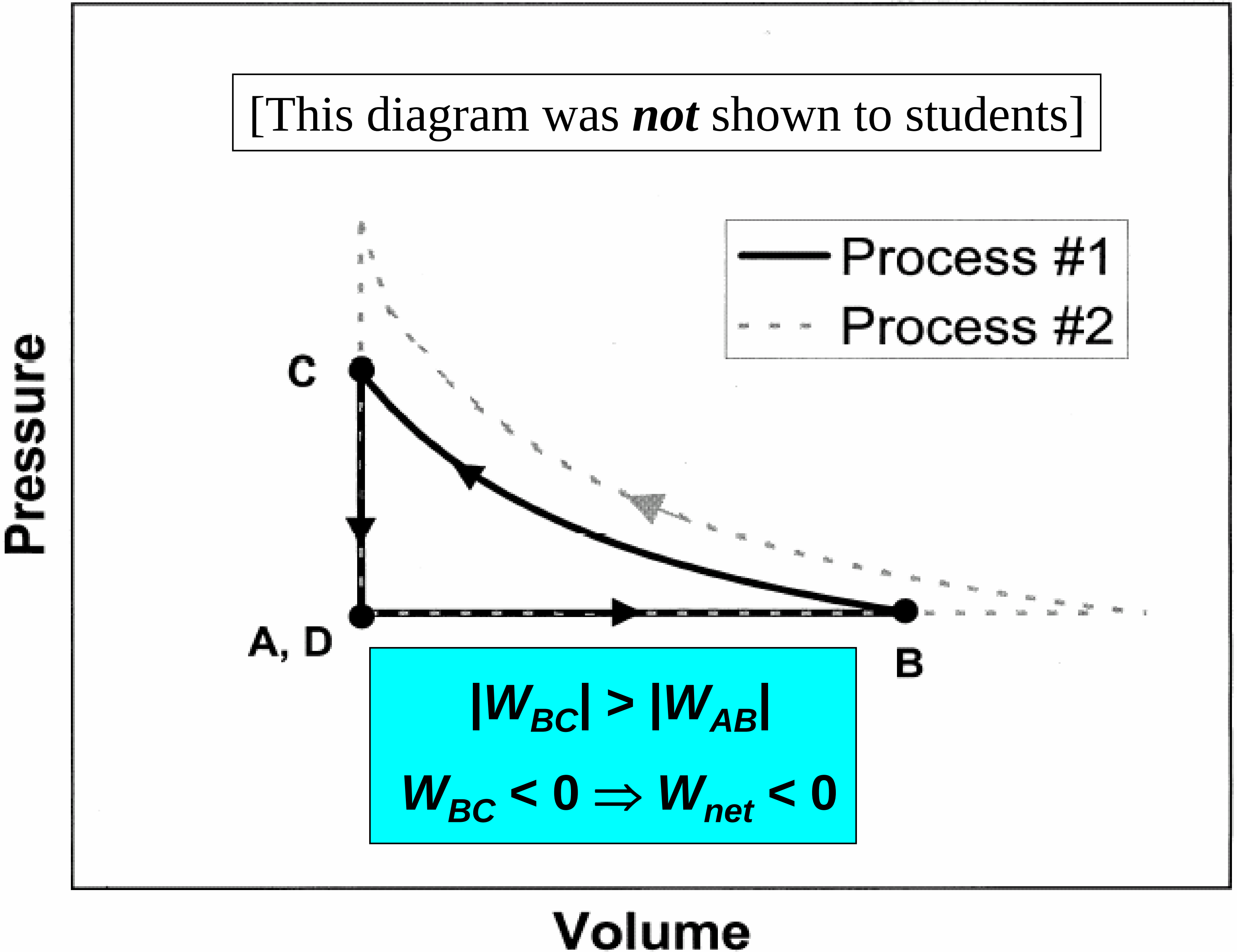
$|W_{BC}| > |W_{AB}|$

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

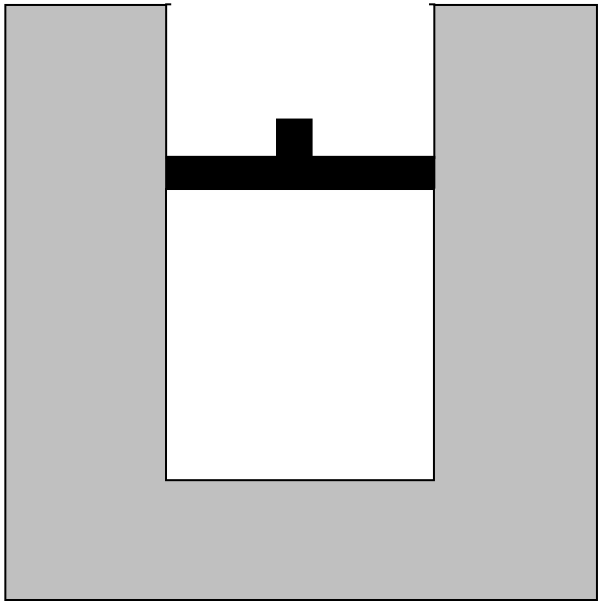


$|W_{BC}| > |W_{AB}|$

$W_{BC} < 0$



[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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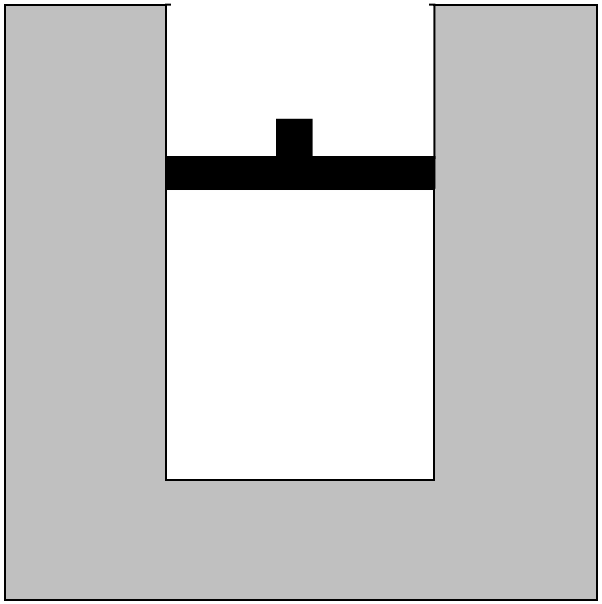

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Results on Question #6 (i)

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

Interview sample *[post-test]**: 19%***

2004 Thermal Physics *[pre-test]**: 10%***

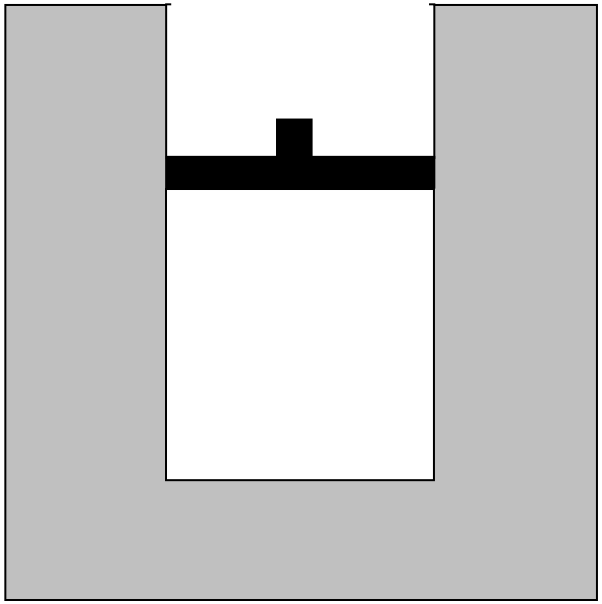
(b) $W_{net} = 0$:

Interview sample *[post-test]**: 63%***

2004 Thermal Physics *[pre-test]**: 45%***

Typical explanation offered for $W_{net} = 0$:

"*The physics definition of work is like force times distance. And basically if you use the same force and you just travel around in a circle and come back to your original spot, technically you did zero work*."



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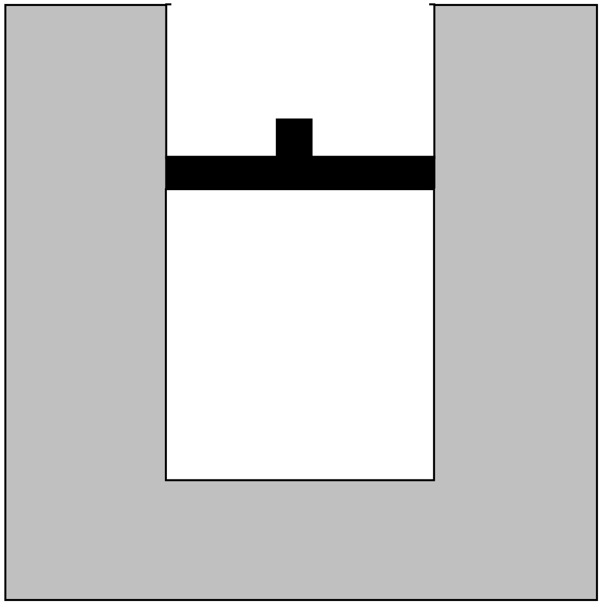

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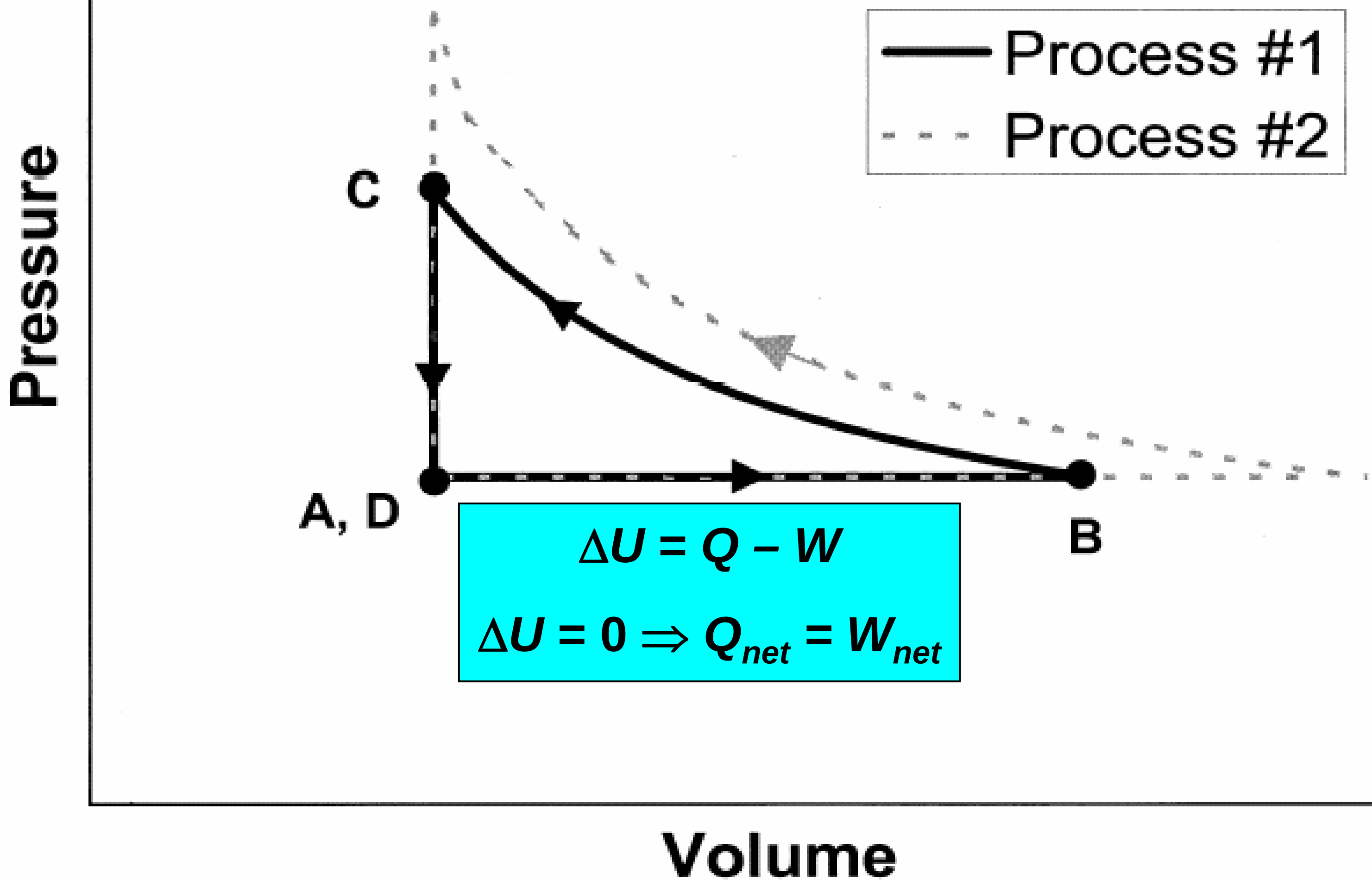
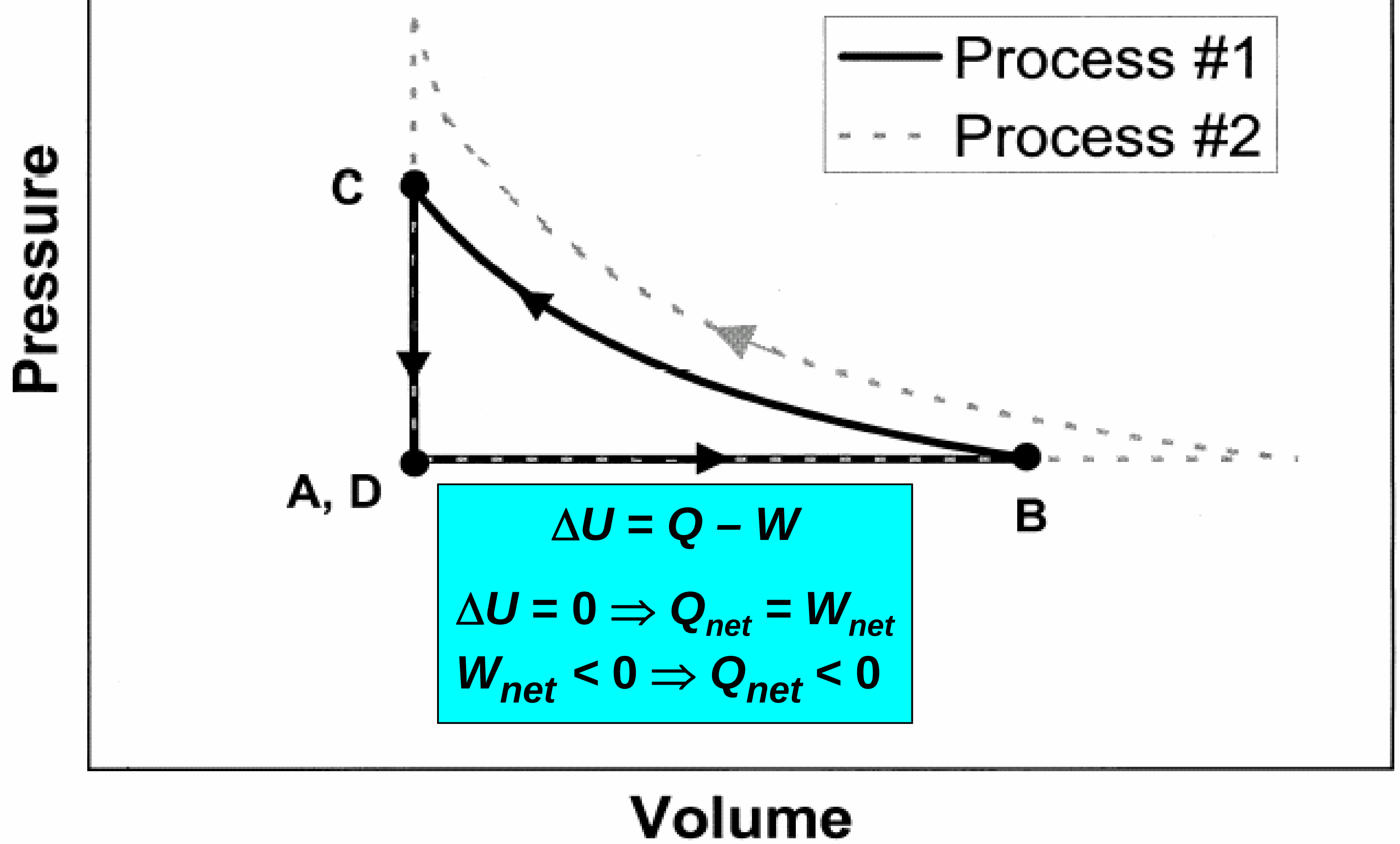


$$\Delta U = Q - W$$

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

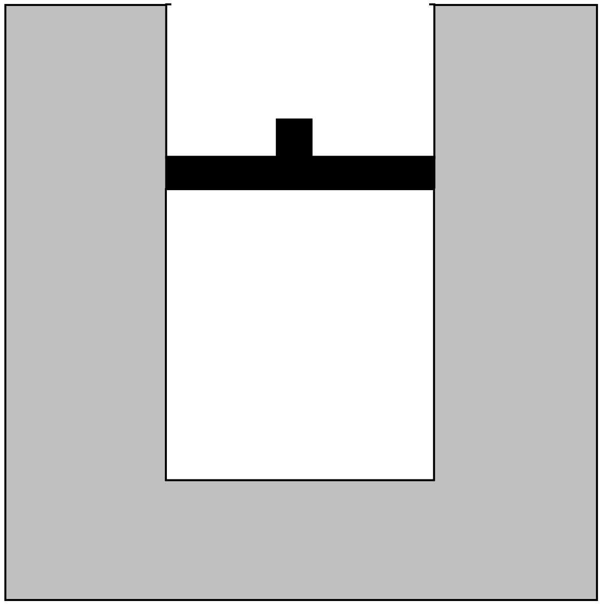
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

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

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



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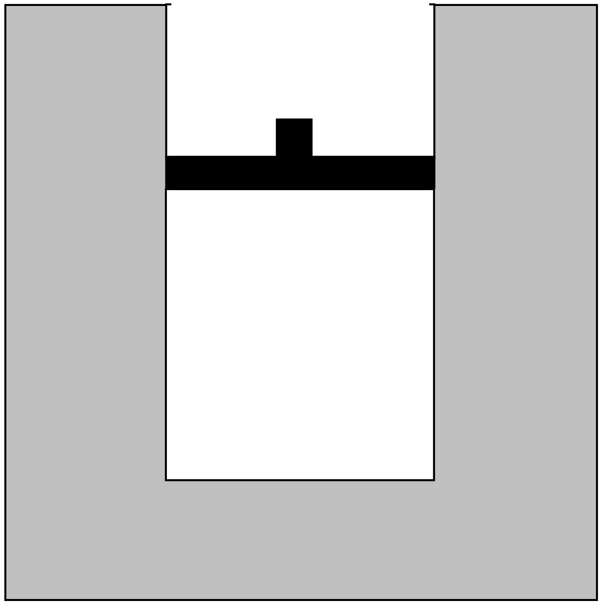

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Results on Question #6 (ii)

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

Interview sample *[post-test]****: 16%***

2004 Thermal Physics *[pre-test]****: 20%***

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

Interview sample *[post-test]****: 69%***

2004 Thermal Physics *[pre-test]****: 80%***

Explanation offered for $Q_{net} = 0$

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"*The heat transferred to the gas . . . is equal to zero . . . . The gas was heated up, but it still returned to its equilibrium temperature. So whatever energy was added to it was distributed back to the room.*"

Explanation offered for $Q_{net} = 0$

"*The heat transferred to the gas . . . is equal to zero . . . . The gas was heated up, but it still returned to its equilibrium temperature. So whatever energy was added to it was distributed back to the room.*"

Common response offered by both introductory and upper-level students

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

- Most students believed that both the net work done ***and*** the total heat transferred would be zero.

- Results for introductory students and upper-level students are consistent.

Some Strategies for Instruction

- Loverude et al.: Solidify students' concept of work in mechanics context (e.g., positive and negative work);
- Develop and emphasize concept of work as an energy-transfer mechanism in thermodynamics context.

Some Strategies for Instruction

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

Some Strategies for Instruction

- Guide students to pay careful attention to *signs* and relative *magnitudes* of work done and heat transferred during different stages of a process.
- Lead students to justify ***why*** net work done and net heat transferred need not equal zero, even when $\Delta V_{\mathrm{process}} = \Delta T_{\mathrm{process}} = 0$.

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

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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 **system** [S_{system}] *increase*, *decrease*, or *remain the same*, or is this not determinable with the given information? ***Explain your answer.***

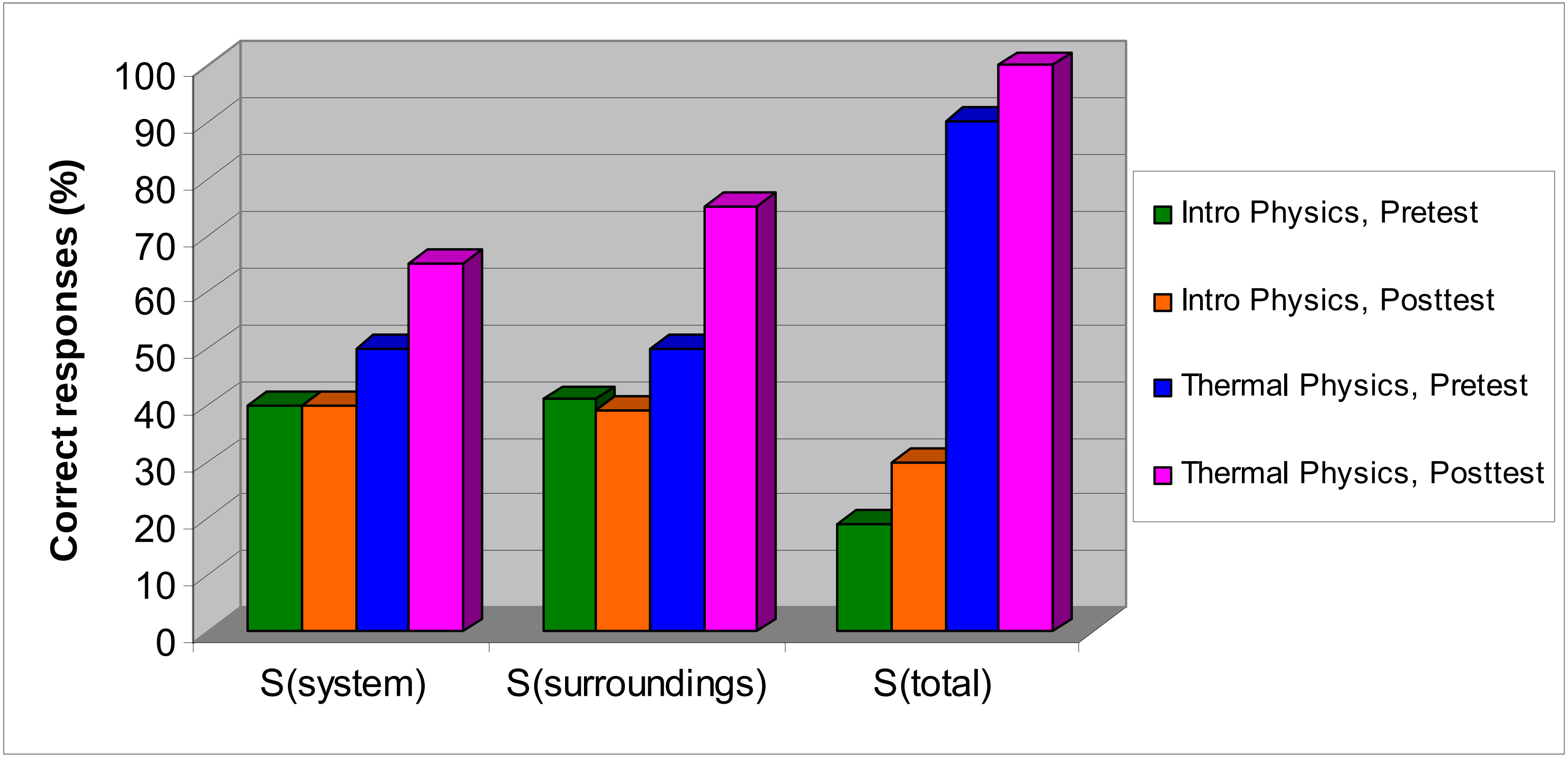
B. During this process, does the entropy of the **surroundings** [$S_{surroundings}$] *increase*, *decrease*, or *remain the same*, or is this not determinable with the given information? ***Explain your answer.***

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.***

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***

Responses to Spontaneous-Process Questions



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

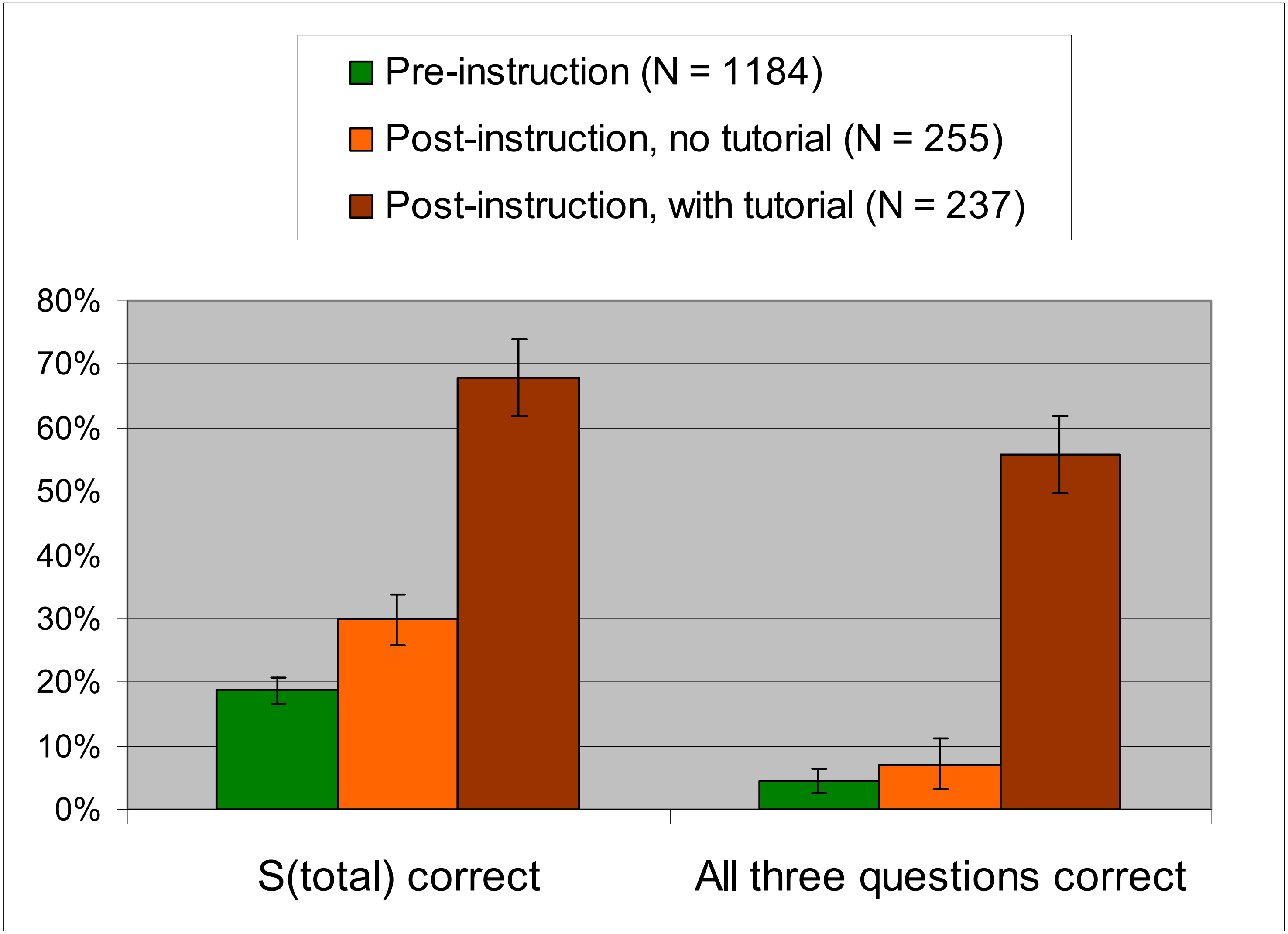
Entropy Worksheet

(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 pipe)
  - 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.

Preliminary results in introductory course are promising…

Responses to Spontaneous-Process Questions Introductory Students



Summary

- Research on student learning lays basis for development of improved instructional materials.

- "Interactive-engagement" instruction using research-based curricula can improve student learning.

- Ongoing development and testing of instructional materials lays the basis for new directions in research, holds promise for sustained improvements in learning.

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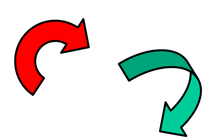

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