Investigating Student Learning and Improving Instruction through Physics Education Research

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Funding

National Science Foundation

Division of Undergraduate Education
Division of Research, Evaluation and Communication
Division of Physics

ISU Center for Teaching Excellence

Miller Faculty Fellowship 1999-2000 (with T. Greenbowe)
CTE Teaching Scholar 2002-2003

Outline

Physics Education as a Research Problem

- Goals and Methods of Physics Education Research
- Some Specific Issues

Research-Based Instructional Methods

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

Research-Based Curriculum Development

- A “model” problem: student understanding of gravitation
- Investigation of 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

Time Burden of Empirical Research

- Many variables (student demographics, instructor style, etc.)
  - hard to estimate relative importance
  - difficult to control

- Fluctuations between data runs tend to be large
  - ➢ increases importance of replication
  - ➢ each data run requires entire semester

“Basic Research” in PER

- Extensive investigations of student reasoning on various topics
- Assess impact of diverse variables
  - student background
  - course logistics

➢ Ultimate impact on improved student learning is often a long-term process.

What PER Can NOT Do

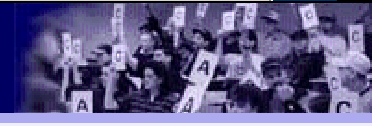
- Determine “philosophical” approach toward undergraduate education
  - e.g., focus on majority of students, or on subgroup?
- Specify the goals of instruction in particular learning environments
  - proper balance among “concepts,” problem-solving, etc.

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

> 11 yrs old	7-11 yrs old	< 7 yrs old
*U. Washington	U. Maine	Oregon State U.
*Kansas State U.	Montana State U.	Iowa State U.
*Ohio State U.	U. Arkansas	City Col. N.Y.
*North Carolina State U.	U. Virginia	Texas Tech U.
*U. Maryland		U. Central Florida
*U. Minnesota		U. Colorado
*San Diego State U. [joint with U.C.S.D.]		U. Illinois
*Arizona State U.		U. Pittsburgh
U. Mass., Amherst		Rutgers U.
Mississippi State U.		Western Michigan U.
U. Oregon		Worcester Poly. Inst.
U. California, Davis		U. Arizona
		New Mexico State U.

*leading producers of Ph.D.'s

Physics Education
Research Group



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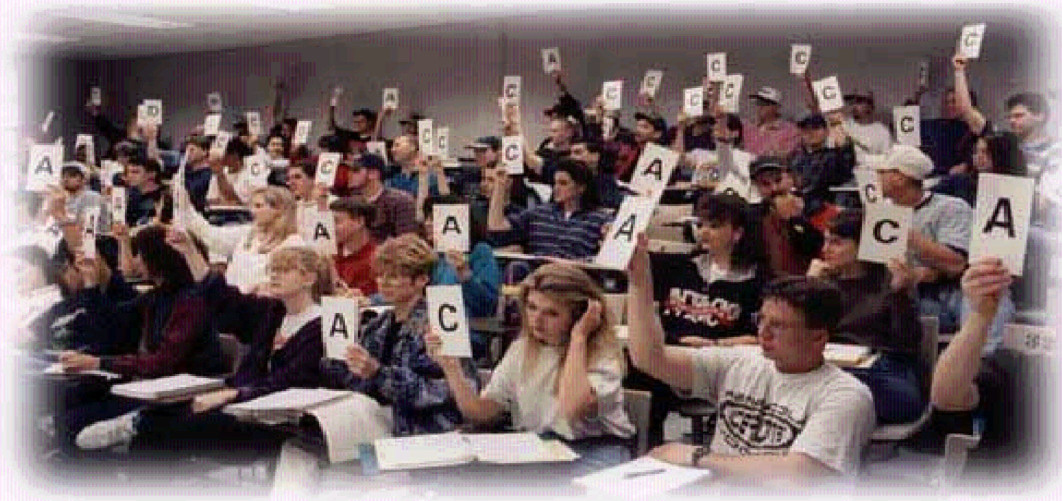

Department of Physics and Astronomy
Iowa State University
Ames, Iowa

Welcome to the website for Iowa State University's Physics Education Research Group! Follow the links on the navigation bar to find out more about our teaching and research.

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Learn about the purpose and goals of Iowa State's PERG.

Members
Find contact information for students and faculty involved in the PERG.

Media
Watch physics education in action at Iowa State.

Links
Find other physics education resources on the web.

Current Projects
Explore the PERG's latest projects.

Publications and Preprints

www.physics.iastate.edu/per/

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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 many questions.
- Use of classroom communication systems to obtain **instantaneous feedback** from entire class.
- Cooperative **group work** using carefully structured 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”)

v

Curriculum Requirements for Fully Interactive Lecture

- Many question sequences employing multiple representations, covering full range of topics
- Free-response worksheets adaptable for use in lecture hall
- Text reference ("Lecture Notes") with strong focus on conceptual and qualitative questions

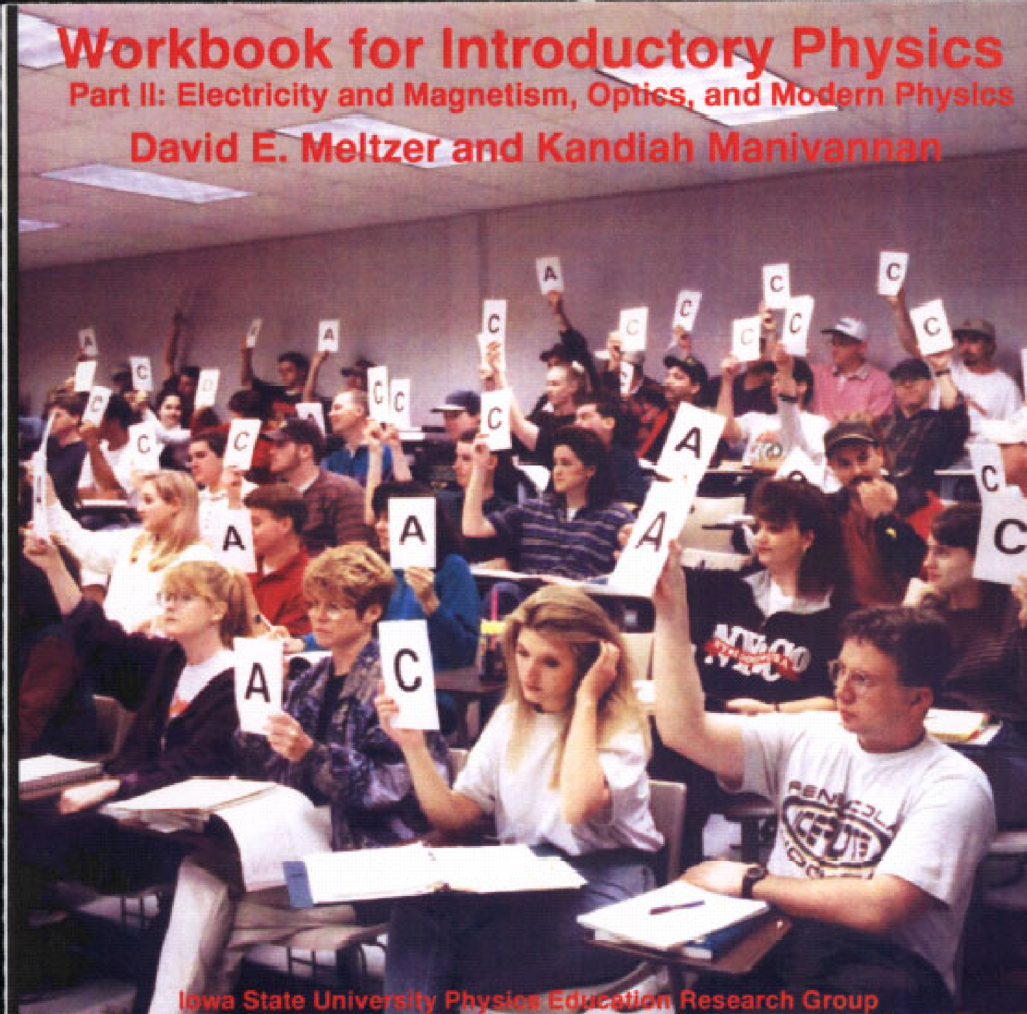
➡ *Workbook for Introductory Physics (DEM and K. Manivannan, CD-ROM, 2002)*

Supported by NSF under "Assessment of Student Achievement" program

Workbook for Introductory Physics

Part II: Electricity and Magnetism, Optics, and Modern Physics

David E. Meltzer and Kandiah Manivannan



Iowa State University Physics Education Research Group

Chapter 1 Electrical Forces

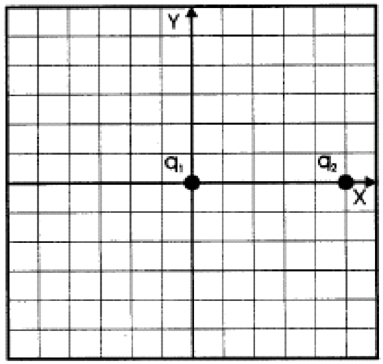
"Flash-Card" Questions

In-Class Questions

Prerequisite Concepts:

- **Positive and negative charges; Coulomb's law: $F = kq_1q_2/r^2$**
- **Protons (+) and electrons (–)**
- **Superposition principle: $F_{net}=F_1+F_2 + . . . + F_n$**
- **Vector addition: $F_{netx}=F_{1x} + F_{2x} + . . . F_{nx}$**
- **Newton's second law, $a = F/m$**

Questions #1–2 refer to the figure below. Charge q_1 is located at the origin, and charge q_2 is located on the positive x axis, five meters from the origin. There are no other charges anywhere nearby.



1. If q_1 is positive and q_2 is negative, what is the direction of the electrical force on q_1?

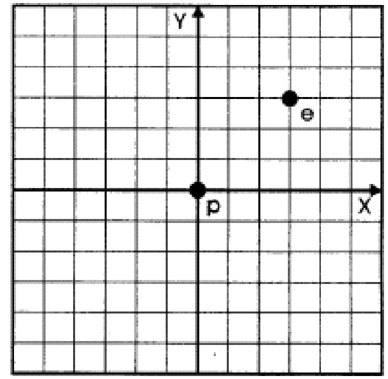
   A. in the positive x direction
   B. in the negative x direction
   C. in the positive y direction
   D. in the negative y direction
   E. the force is not directed precisely along any of the coordinate axes, but at some angle
   F. there is no force in this case

2. If q_1 is positive and q_2 is positive, what is the direction of the electrical force on q_1?

   A. in the positive x direction
   B. in the negative x direction
   C. in the positive y direction
   D. in the negative y direction
   E. the force is not directed precisely along any of the coordinate axes, but at some angle
   F. there is no force in this case

“Flash-Card” Questions

3. In this figure, a proton is located at the origin, and an electron is located at the point (3m, 3m). What is the direction of the electrical force on the proton?



A. 

B. 

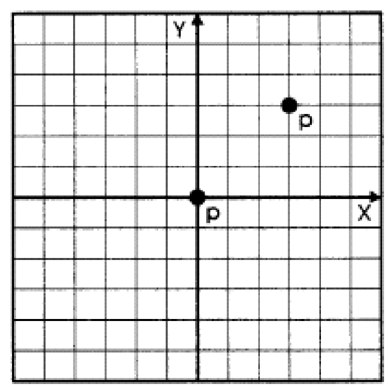
C. 

D. 

E. 

F. 

4. In this figure, a proton is located at the origin, and a proton is located at the point (3m, 3m). The vector representing the electrical force on the proton *at the origin* makes what angle with respect to the positive x axis?



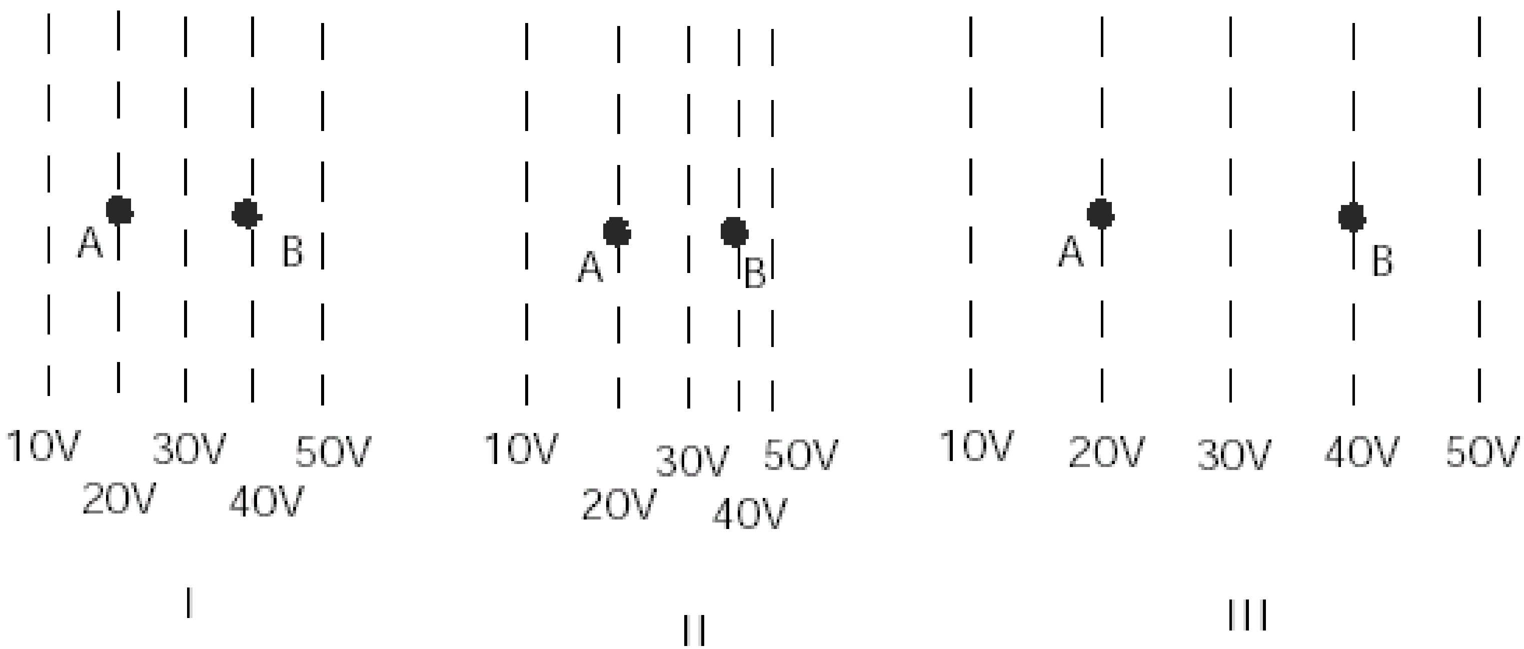
A. 0°
B. 45°
C. 90°
D. 135°
E. 225°
F. 270°

Assessment Data

Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	***N***
National sample (algebra-based)	402
National sample (calculus-based)	1496

In the figures below, the dotted lines show the equipotential lines of electric fields. (A charge moving along a line of equal potential would have a constant electric potential energy.) A charged object is moved directly from point A to point B. The charge on the object is +1 μC.



1. How does the magnitude of the electric field at B compare for these three cases?
   (a) I > III > II
   (b) I > II > III
   (c) III > I > II
   (d) II > I > III
   (e) I = II = III

D. Maloney, T. O'Kuma, C. Hieggelke, and A. Van Heuvelen, PERS of Am. J. Phys. ***69****, S12 (2001).*

Assessment Data

Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	*N*
National sample (algebra-based)	402
National sample (calculus-based)	1496

Assessment Data

Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	*N*	Mean pre-test score
National sample (algebra-based)	402	**27%**
National sample (calculus-based)	1496	

Assessment Data

Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	***N***	**Mean pre-test score**
National sample (algebra-based)	402	**27%**
National sample (calculus-based)	1496	**37%**

Assessment Data

Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	*N*	Mean pre-test score	Mean post-test score
National sample (algebra-based)	402	**27%**	**43%**
National sample (calculus-based)	1496	**37%**	**51%**

Assessment Data

Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	*N*	Mean pre-test score	Mean post-test score
National sample (algebra-based)	402	27%	43%
National sample (calculus-based)	1496	37%	51%
ISU 1998	70	30%	
ISU 1999	87	26%	
ISU 2000	66	29%	

Assessment Data

Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	*N*	Mean pre-test score	Mean post-test score
National sample (algebra-based)	402	**27%**	**43%**
National sample (calculus-based)	1496	**37%**	**51%**
ISU 1998	70	**30%**	**75%**
ISU 1999	87	**26%**	**79%**
ISU 2000	66	**29%**	**79%**

Quantitative Problem Solving: Are skills being sacrificed?

ISU Physics 112 compared to ISU Physics 221 (calculus-based), numerical final exam questions on electricity

Quantitative Problem Solving: Are skills being sacrificed?

ISU Physics 112 compared to ISU Physics 221 (calculus-based), numerical final exam questions on electricity

	N	**Mean Score**
Physics 221: F97 & F98 ***Six final exam questions***	*320*	
Physics 221: F97 & F98 **Subset of three questions**	*372*	

Quantitative Problem Solving: Are skills being sacrificed?

ISU Physics 112 compared to ISU Physics 221 (calculus-based), numerical final exam questions on electricity

	N	**Mean Score**
Physics 221: F97 & F98 ***Six final exam questions***	*320*	56%
Physics 221: F97 & F98 **Subset of three questions**	*372*	59%

Quantitative Problem Solving: Are skills being sacrificed?

ISU Physics 112 compared to ISU Physics 221 (calculus-based), numerical final exam questions on electricity

	N	Mean Score
Physics 221: F97 & F98 ***Six final exam questions***	*320*	56%
Physics 112: F98 **Six final exam questions**	*76*	
Physics 221: F97 & F98 **Subset of three questions**	*372*	59%
Physics 112: F98, F99, F00 **Subset of three questions**	*241*	

Quantitative Problem Solving: Are skills being sacrificed?

ISU Physics 112 compared to ISU Physics 221 (calculus-based), numerical final exam questions on electricity

	N	Mean Score
Physics 221: F97 & F98 ***Six final exam questions***	*320*	56%
Physics 112: F98 **Six final exam questions**	*76*	77%
Physics 221: F97 & F98 **Subset of three questions**	*372*	59%
Physics 112: F98, F99, F00 **Subset of three questions**	*241*	78%

Challenges to Implementation

- Many (most?) students are comfortable and familiar with more passive methods of learning science. ***Active learning methods are always challenging, and frequently frustrating for students. Some (many?) react with anger.***

- Active learning methods and curricula are not "instructor proof." Training, experience, energy and commitment are needed to use them effectively.

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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

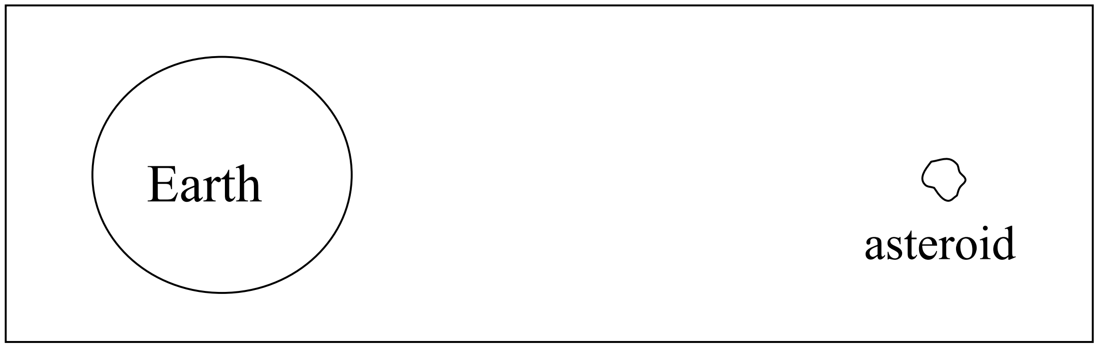
Student Concepts of Gravitation

[Jack Dostal and DEM]

- 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.*

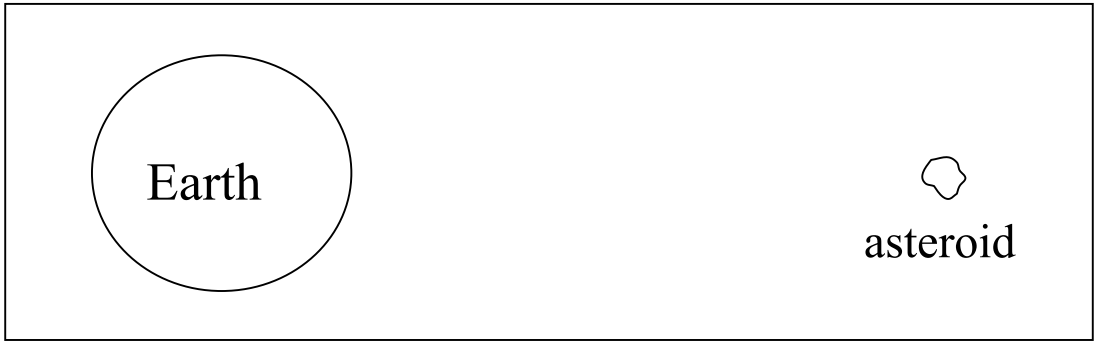
- Worksheets developed to address learning difficulties; tested in calculus-based physics course Fall 1999

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.*

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



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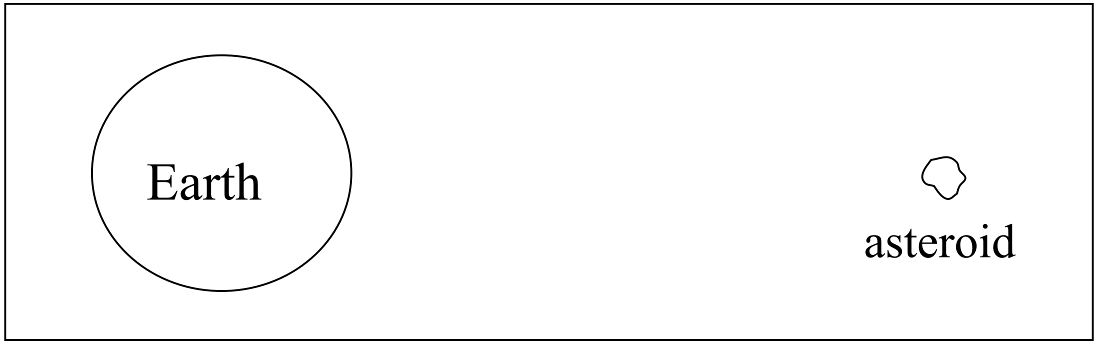

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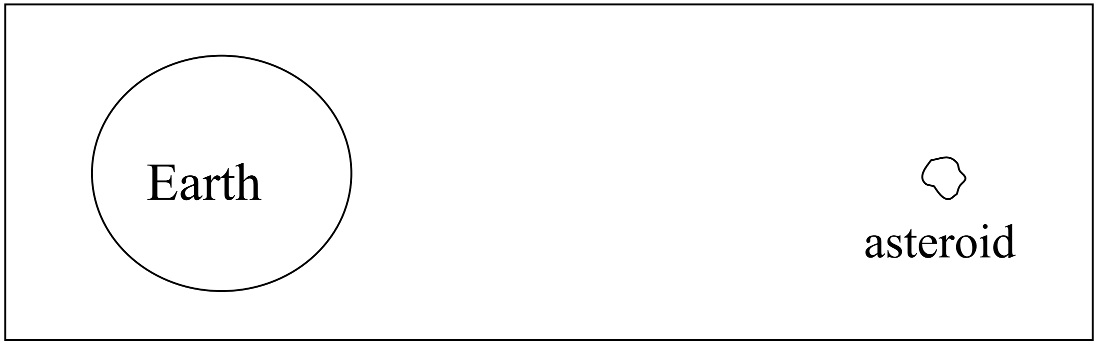

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First-semester Physics *(N = 546)*: ***15% correct responses***

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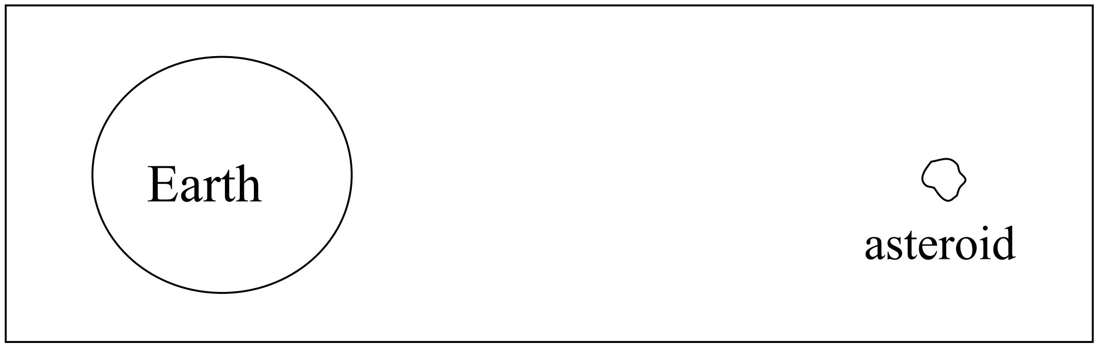

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Second-semester Physics *(N = 414)*: ***38% correct responses***

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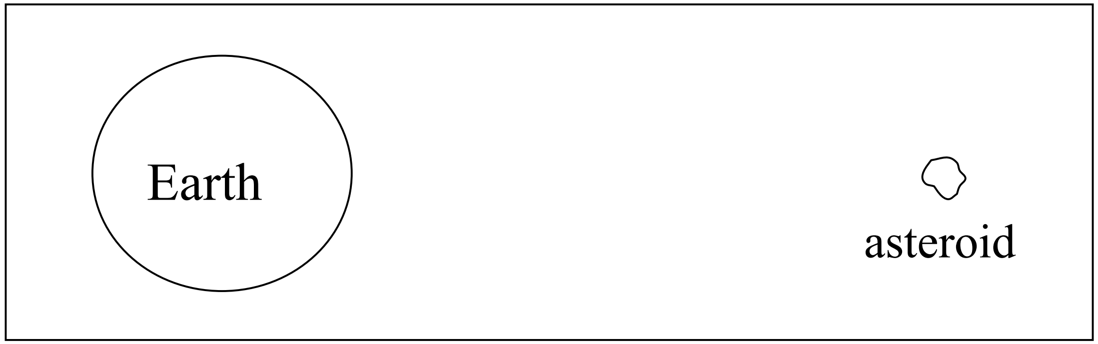

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Most students claim that Earth exerts greater force because it is larger

Implementation of Instructional Model

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

- Guide students through reasoning process in which they tend to encounter targeted conceptual difficulty
- Allow students to commit themselves to a response that reflects conceptual difficulty
- Guide students along alternative 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*

- 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

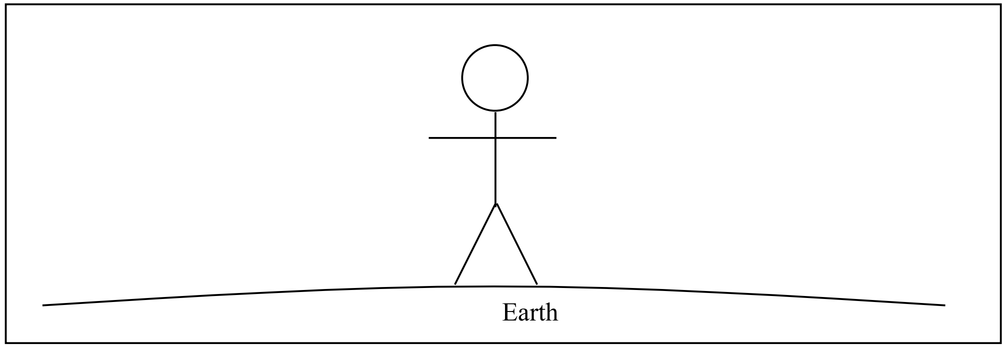
Protocol for Testing Worksheets
(Fall 1999)

- 30% of recitation sections yielded half of one period for students to do worksheets
- Students work in small groups, instructors circulate
- No net additional instructional time on gravitation
- Conceptual questions added to final exam with instructor's approval

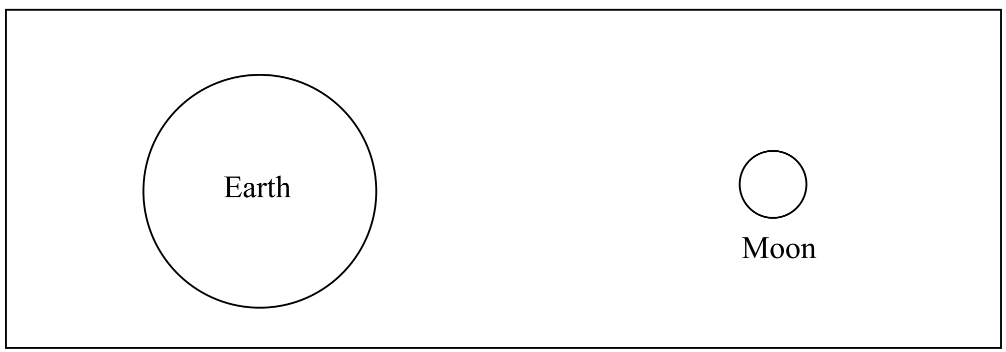
Name________________________

Gravitation Worksheet
Physics 221

a) In the picture below, a person is standing on the surface of the Earth. Draw an arrow (a vector) to represent the force exerted ***by*** the Earth ***on*** the person.



b) In the picture below, both the Earth and the Moon are shown. Draw an arrow to represent the force exerted ***by*** the Earth ***on*** the Moon. Label this arrow **(b)**.



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)**.

d) Are arrows **(b)** and **(c)** the same size? Explain why or why not.

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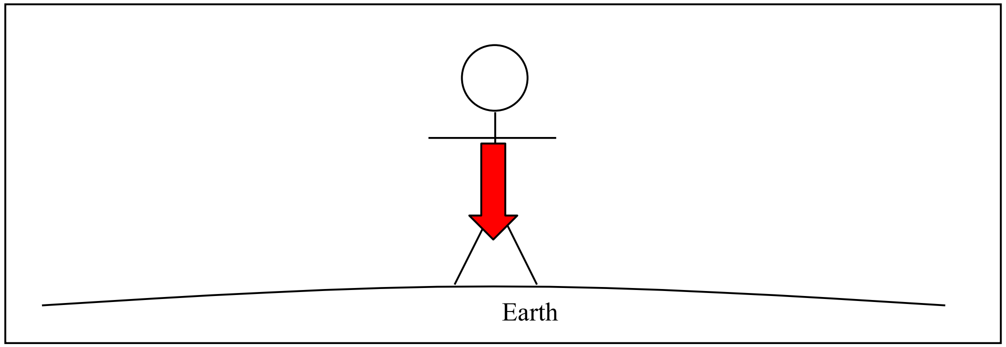

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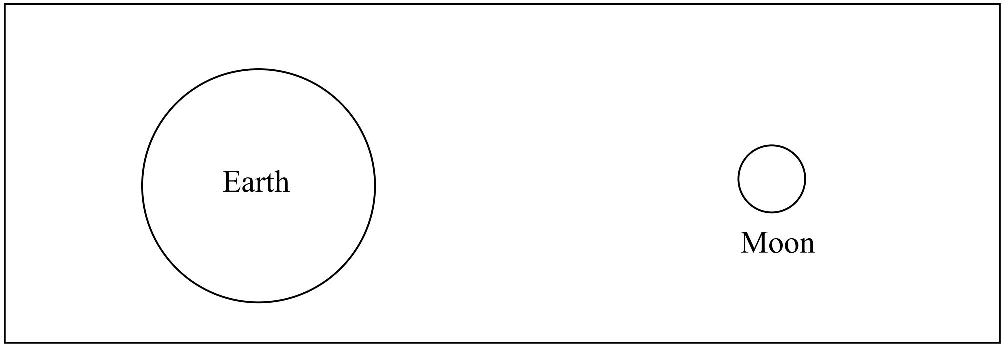

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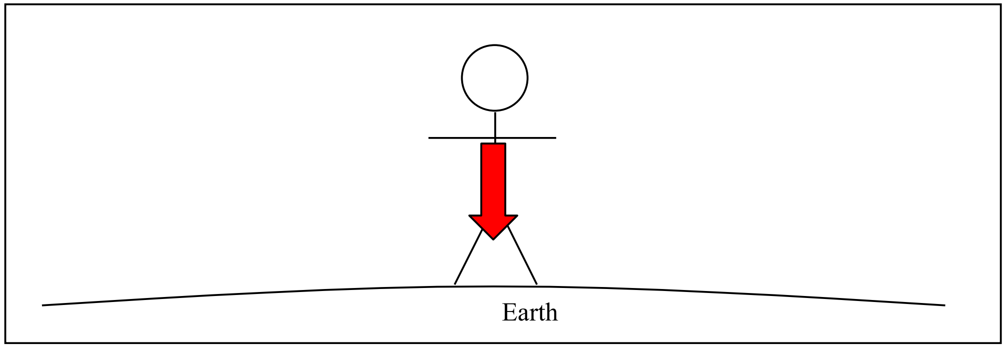

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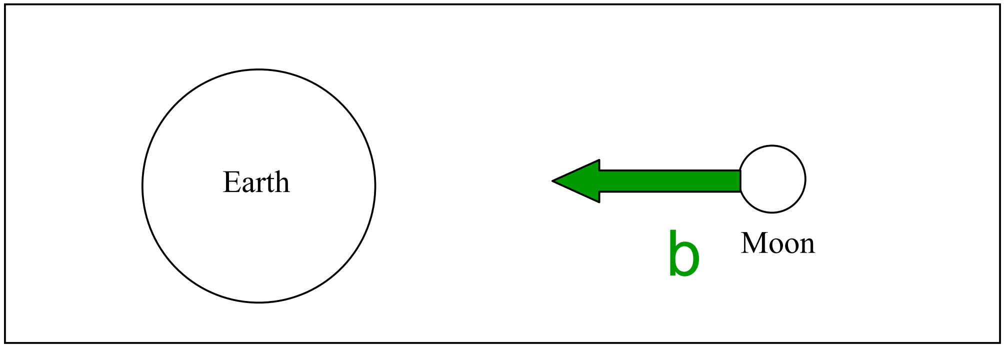

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d) Are arrows **(b)** and **(c)** the same size? Explain why or why not.

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Gravitation Worksheet
Physics 221

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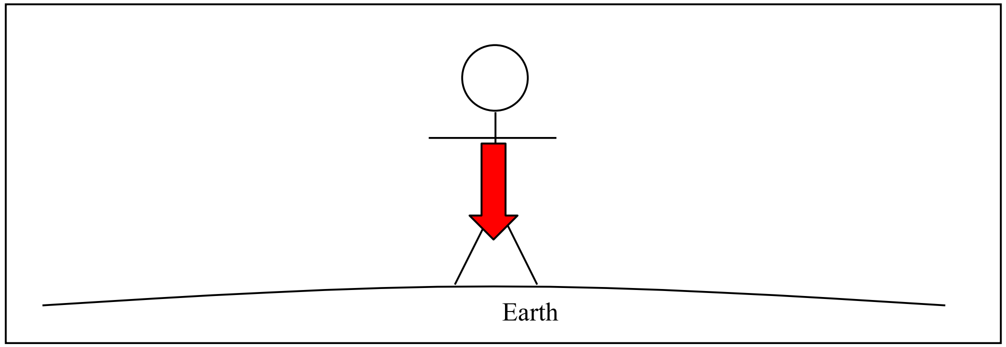

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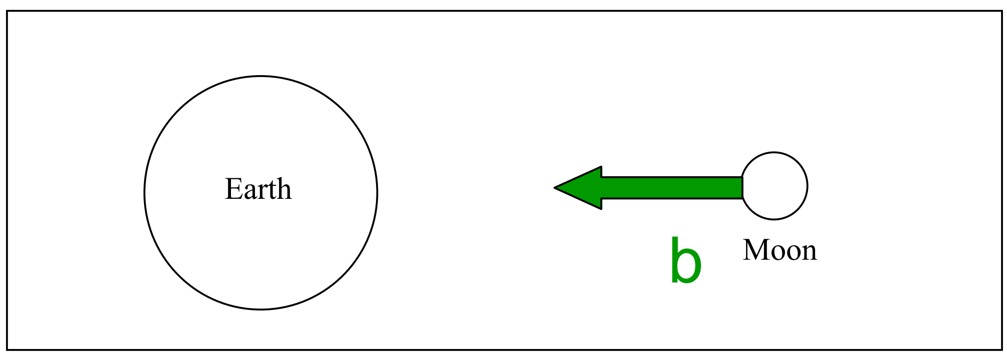

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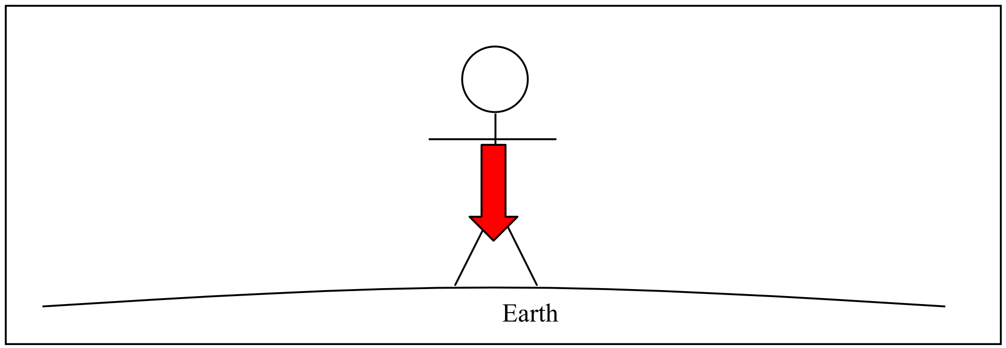

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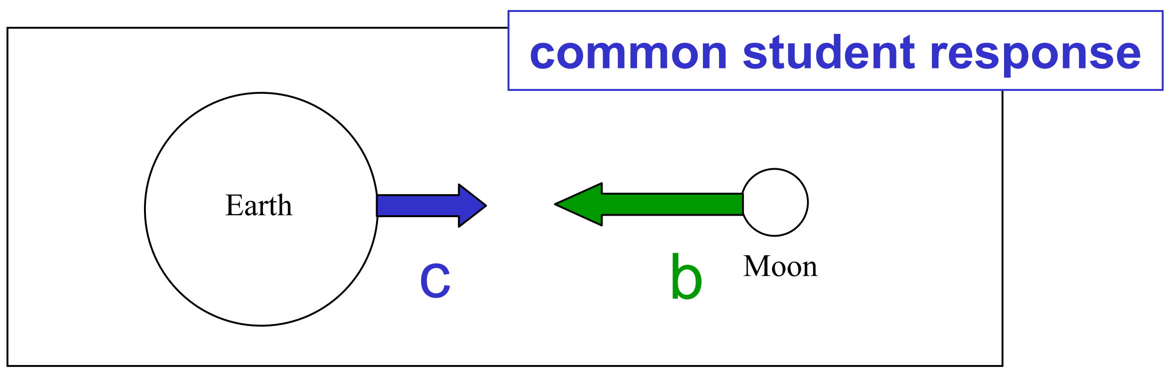

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e) Consider the magnitude of the gravitational force in (b). Write down an algebraic expression for the strength of the force. (Refer to Newton's Universal Law of Gravitation at the top of the previous page.) Use M_e for the mass of the Earth and M_m for the mass of the Moon.

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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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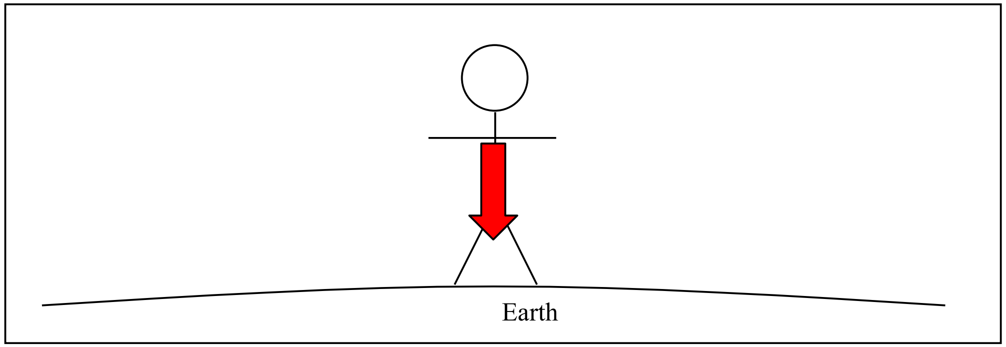

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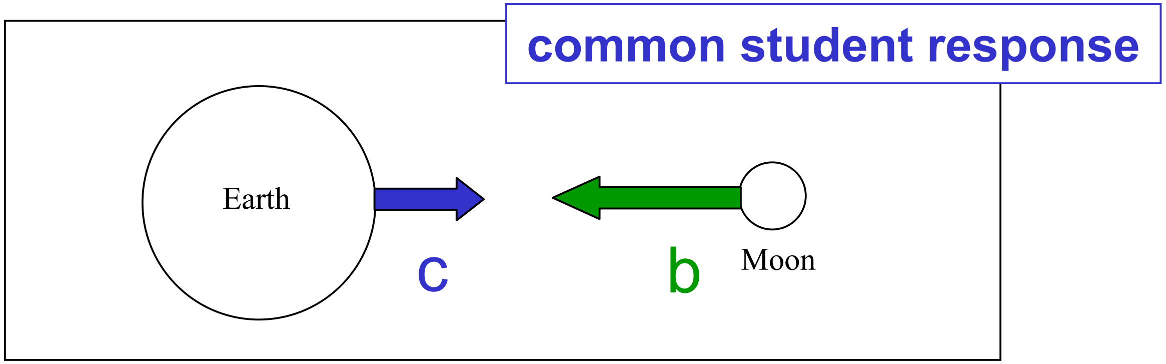

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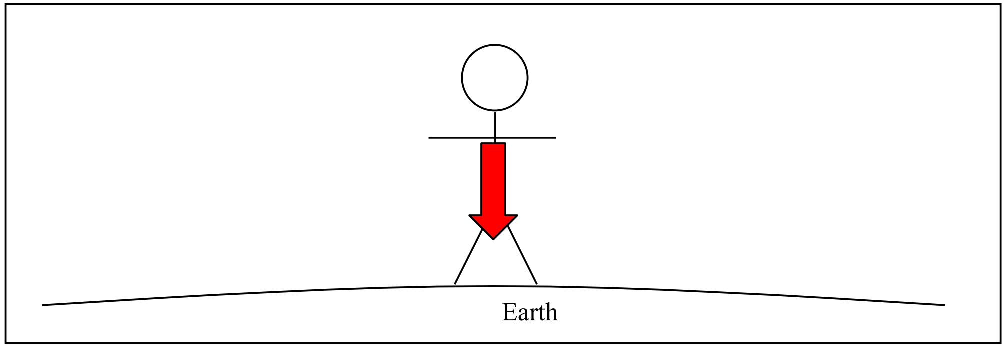

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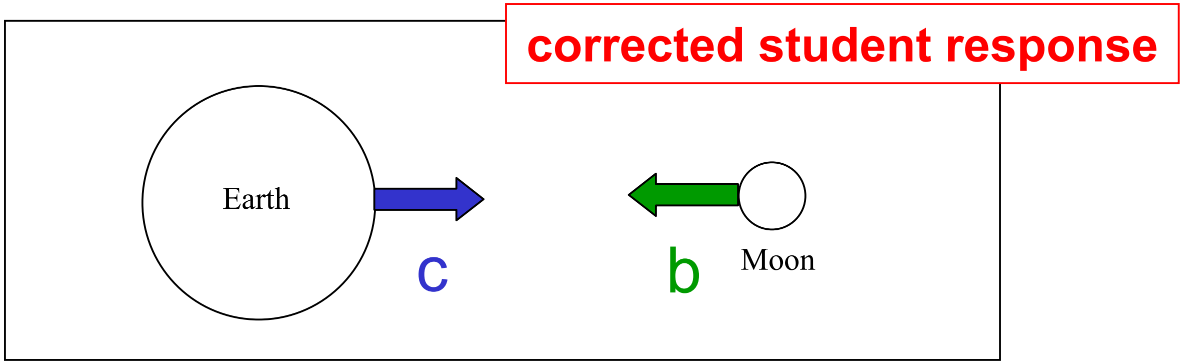

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2) In the following diagrams, draw arrows representing force vectors, such that the length of the arrow is proportional to the magnitude of the force it represents.

Diagram (i): In this figure, two equal spherical masses (mass = "M") are shown. Draw the vectors representing the gravitational forces the masses exert on each other. Draw your *shortest* vector to have a length equal to *one* of the grid squares.

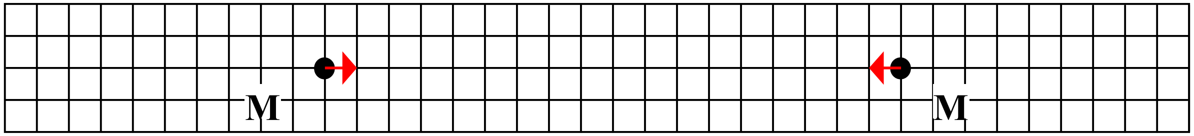


Diagram (ii): Now, one of the spheres is replaced with a sphere of mass 2M. Draw a new set of vectors representing the mutual gravitational forces in this case.

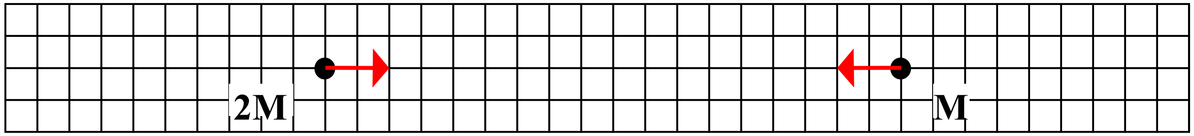
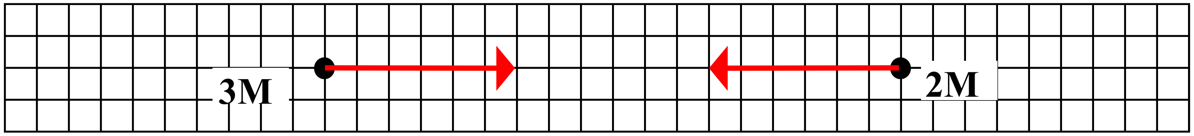


Diagram (iii): In this case, the spheres have masses 2M and 3M. Again, draw the vectors representing the mutual gravitational forces.



Final Exam Question #1

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?

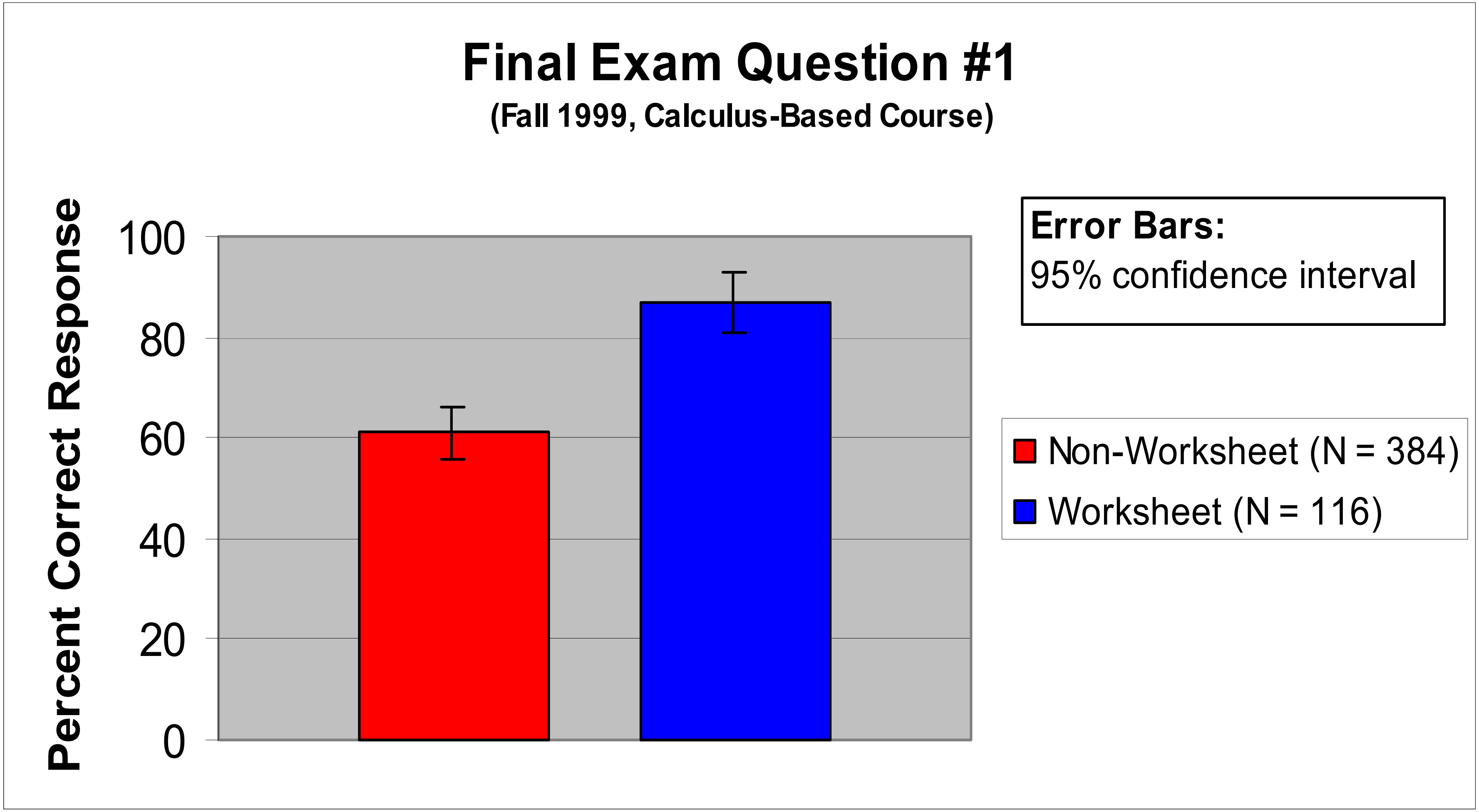
A. The gravitational force exerted by the chunk of ice on Saturn is **greater than** the gravitational force exerted by Saturn on the chunk of ice.

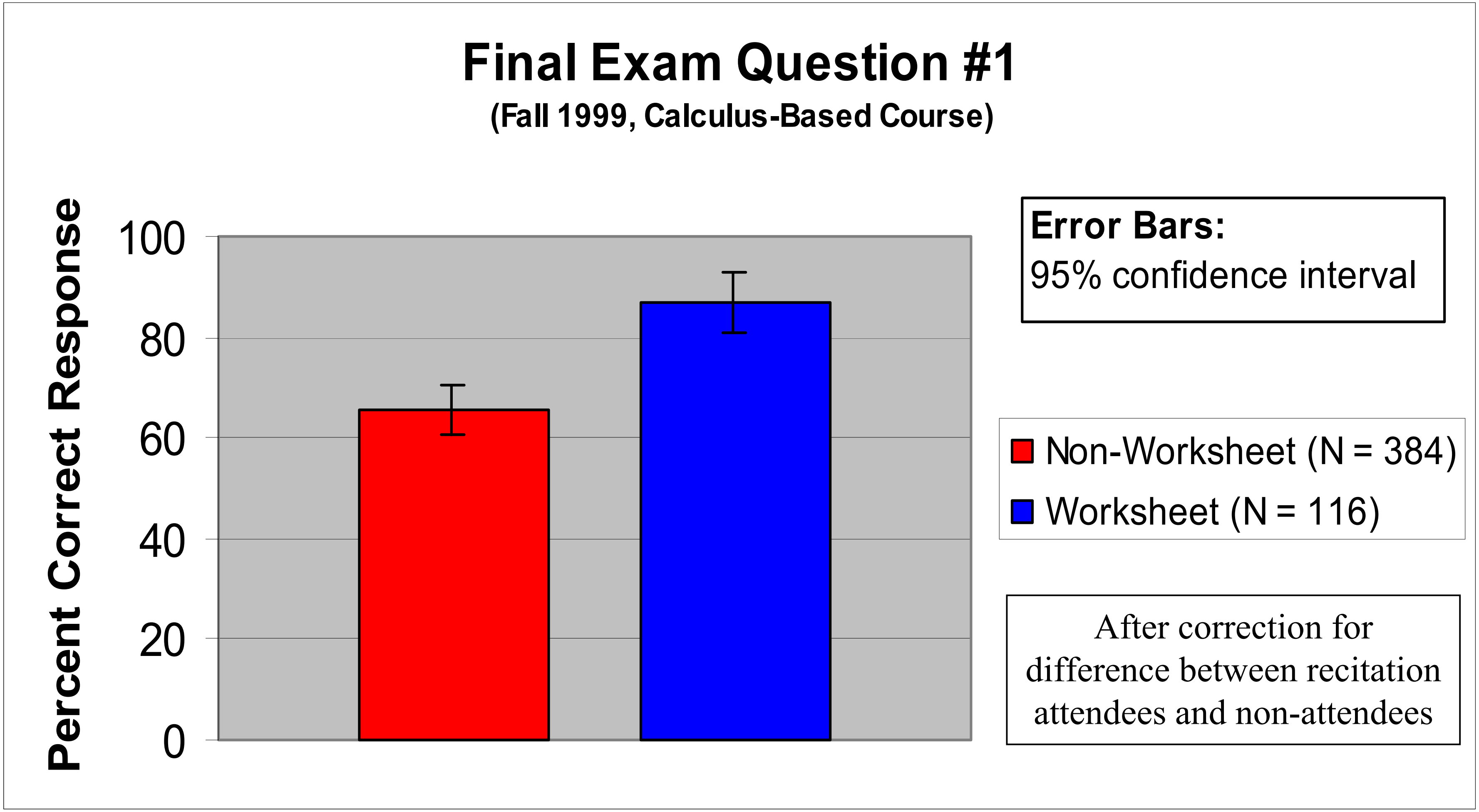
➡ B. The gravitational force exerted by the chunk of ice on Saturn is **the same magnitude as** the gravitational force exerted by Saturn on the chunk of ice.

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.

D. The gravitational force exerted by the chunk of ice on Saturn is zero.

E. Not enough information is given to answer this question.


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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After correction for difference between recitation attendees and non-attendees

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 $2r$. Then, the magnitudes of the gravitational forces experienced by the masses are:

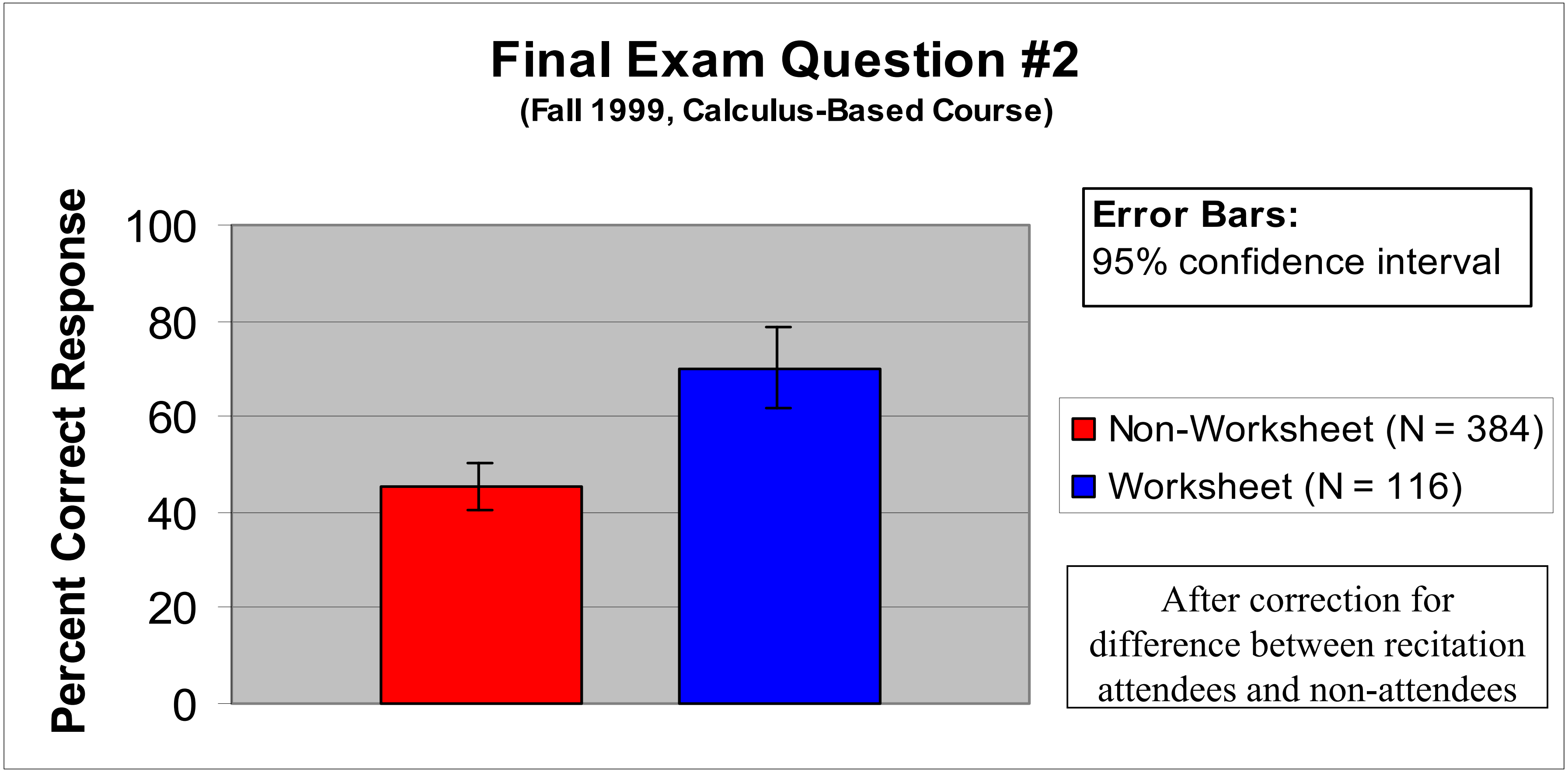
A. equal, and are equal to *F.*

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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Outline

Physics Education as a Research Problem

- Goals and Methods of Physics Education Research
- Some Specific Issues

Research-Based Instructional Methods

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

Research-Based Curriculum Development

- A “model” problem: student understanding of gravitation
- Investigation of student reasoning in thermodynamics

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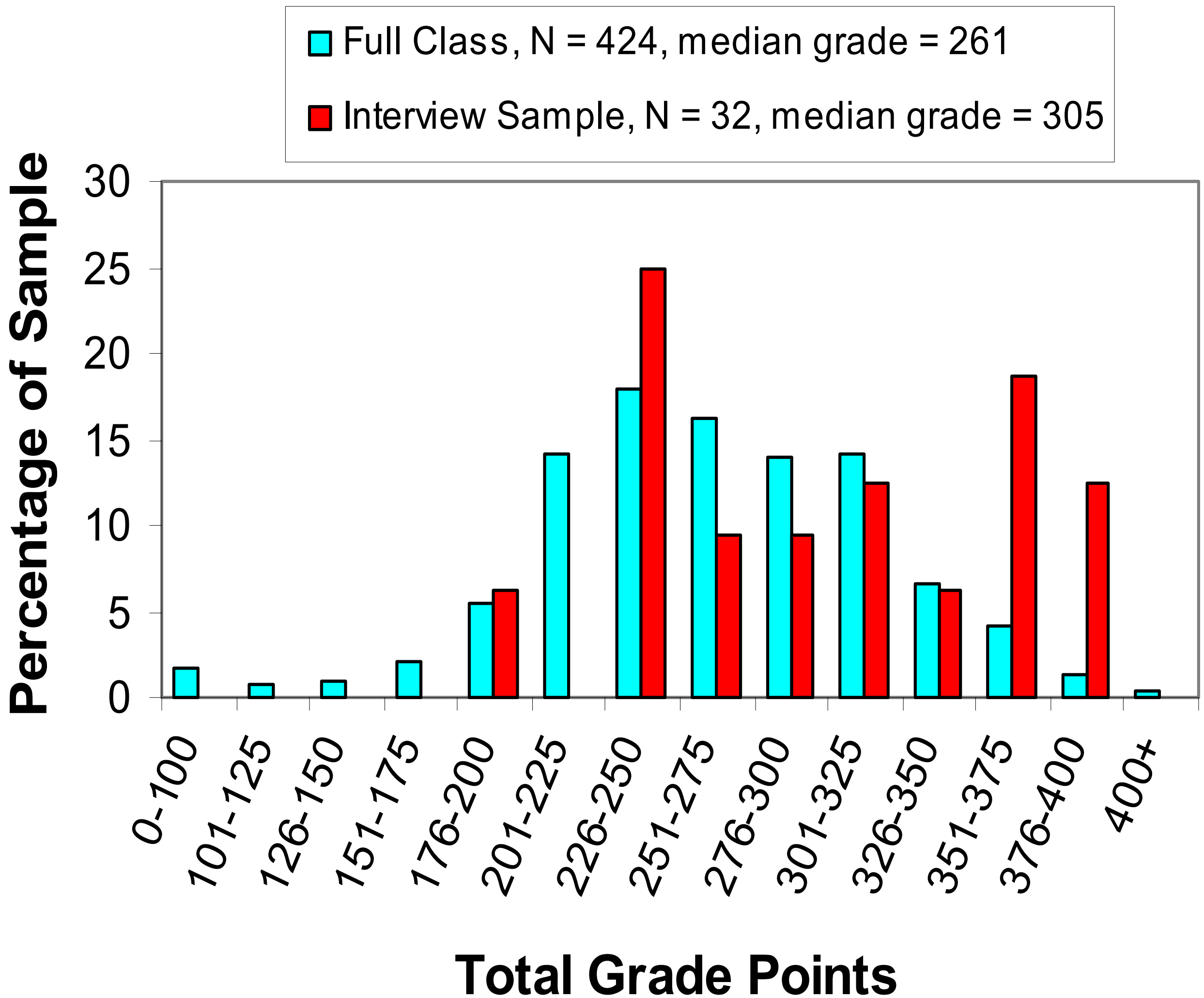
Summary

Thermodynamics Curriculum Project

(NSF CCLI Project with T. Greenbowe)

- Investigation of second-semester calculus-based physics course (mostly engineering students).
- Written diagnostic questions administered last week of class in 1999, 2000, and 2001 (N_{total} = 653).
- Detailed interviews (avg. duration ≥ one hour) carried out with 32 volunteers during 2002 (total class enrollment: 424).
  - *interviews carried out after all thermodynamics instruction completed*
  - *final grades of interview sample far above class average*

Grade Distributions: Interview Sample vs. Full Class



***Interview Sample*:**
34% above 91st percentile; 50% above 81st percentile

Predominant Themes of Students' Reasoning

1. Understanding of concept of state function in the context of energy.
2. Belief that work is a state function.
3. Belief that heat is a state function.
4. Belief that net work done and net heat transferred during a cyclic process are zero.
5. Inability to apply the first law of thermodynamics.

DEM, *Am. J. Phys*. **72**, 1432-1446 (2004)

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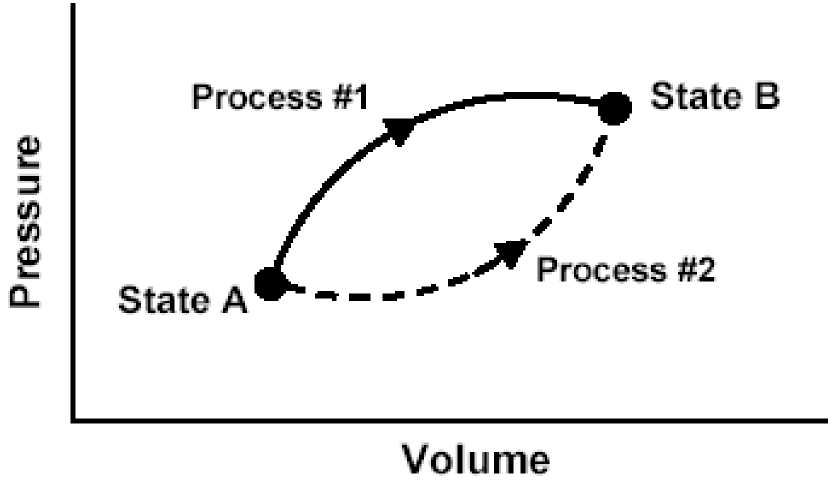
Understanding of Concept of State Function in the Context of Energy

- Diagnostic question: two different processes connecting identical initial and final states.
- Do students realize that only initial and final states determine change in a state function?

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



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

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

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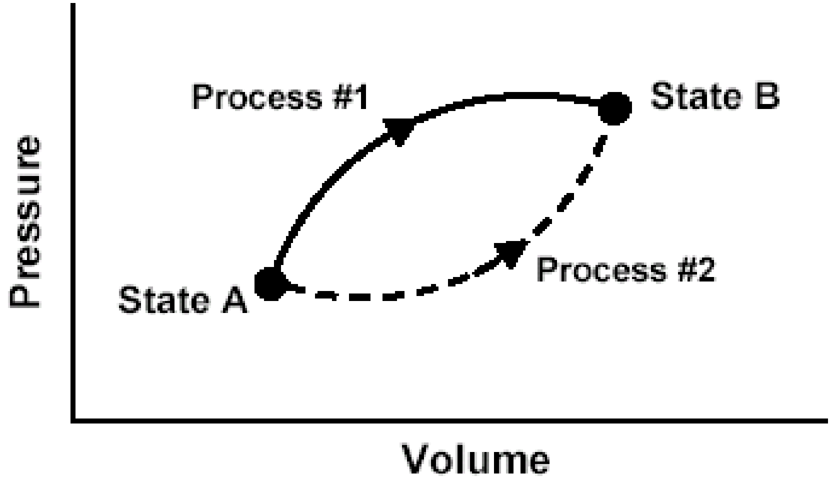

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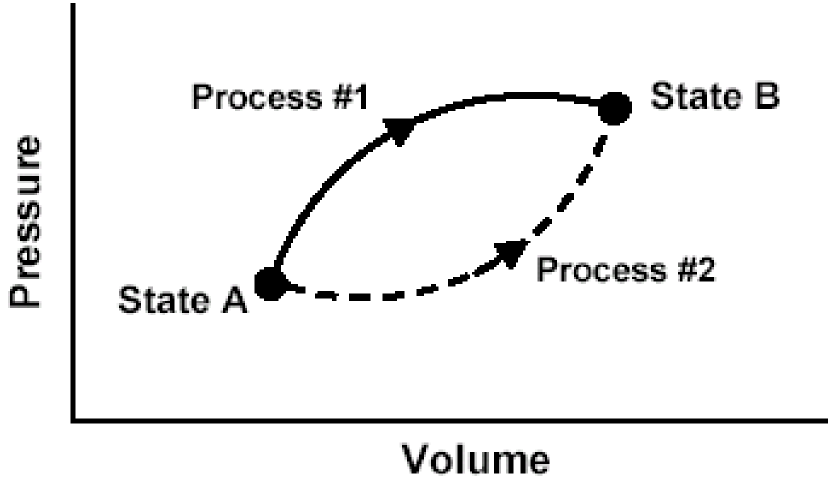

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Students seem to have adequate grasp of state-function concept in *this* context

- Consistently high percentage (70-90%) of correct responses on written question with good explanations.
- Interview subjects displayed good understanding of state-function idea.

➡ Students' major conceptual difficulties stemmed from ***overgeneralization*** of state-function concept. Details to follow…

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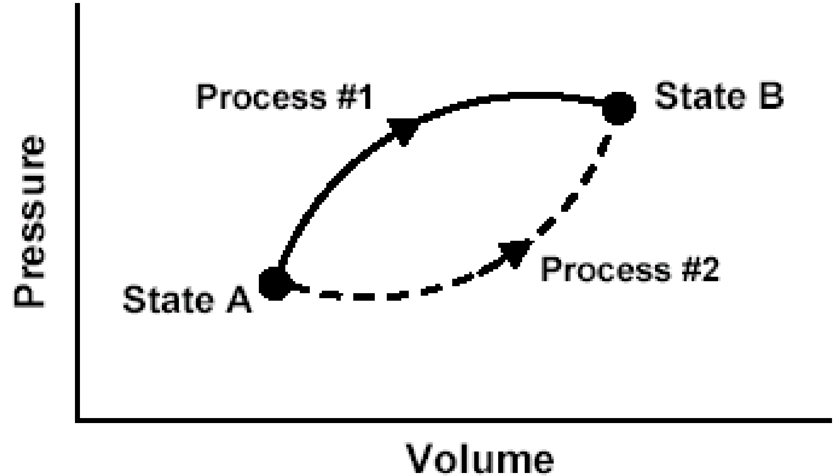

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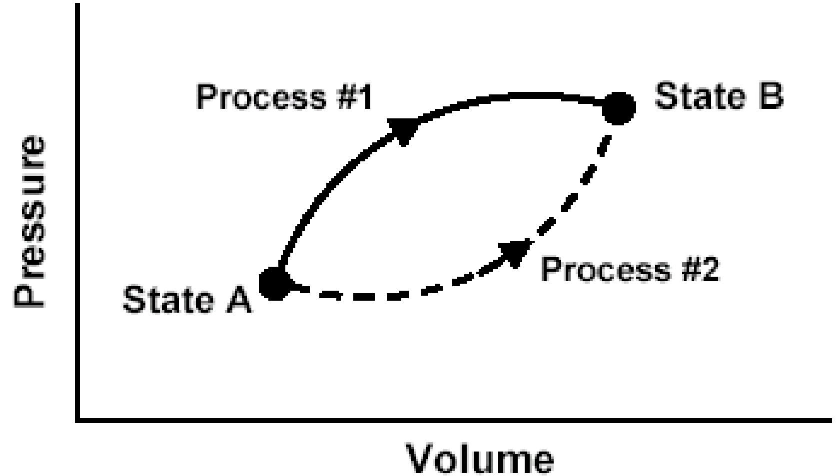

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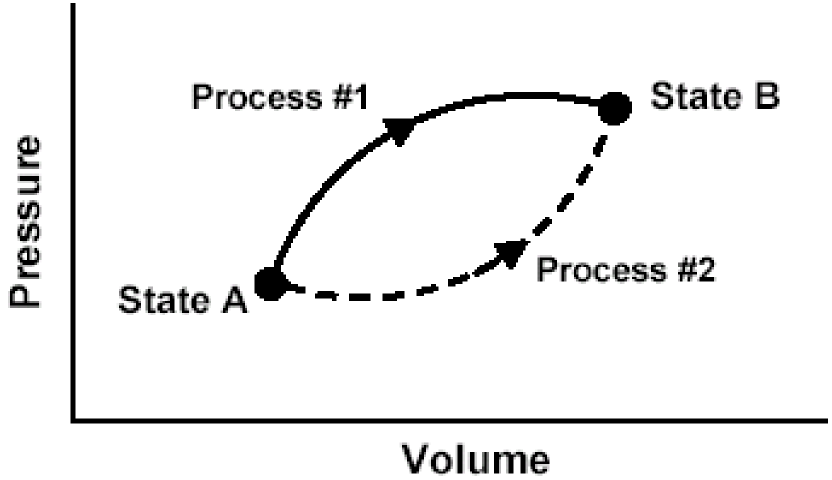

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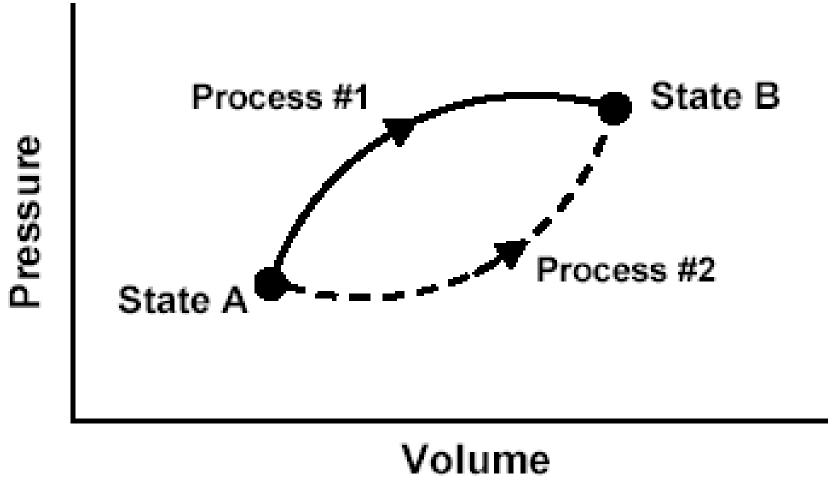

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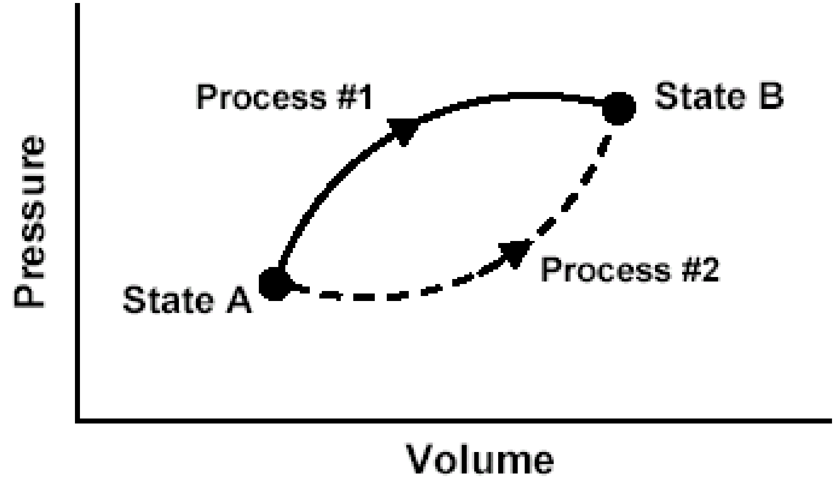

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Responses to Diagnostic Question #1
(Work question)

	1999 (*N*=186)	**2000 (*N*=188)**	**2001 (*N*=279)**	**2002 Interview Sample (*N*=32)**
$W_1 > W_2$				
$W_1 = W_2$				
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	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
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Because work is independent of path	*	14%	23%	

*explanations not required in 1999

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Because work is independent of path	*	14%	23%	22%
Other reason, or none	*	12%	13%	0%

*explanations not required in 1999

Explanations Given by Interview Subjects to Justify $W_1 = W_2$

- "*Work is a state function*."
- "*No matter what route you take to get to state B from A, it's still the same amount of work*."
- "*For work done take state A minus state B; the process to get there doesn't matter*."

➡ **Many students come to associate work with properties (and descriptive phrases) only used by instructors in connection with state functions.**

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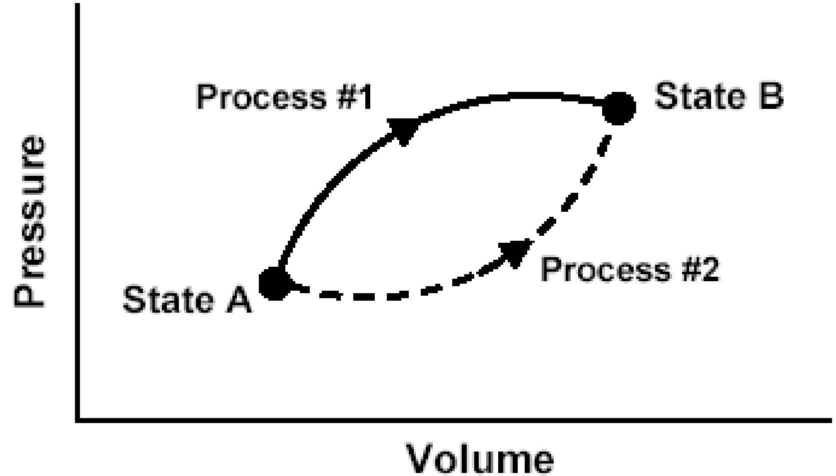
Confusion with mechanical work done by conservative forces?

Predominant Themes of Students' Reasoning

1. Understanding of concept of state function in the context of energy.
2. Belief that work is a state function.
3. Belief that heat is a state function.
4. Belief that net work done and net heat transferred during a cyclic process are zero.
5. Inability to apply the first law of thermodynamics.

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



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

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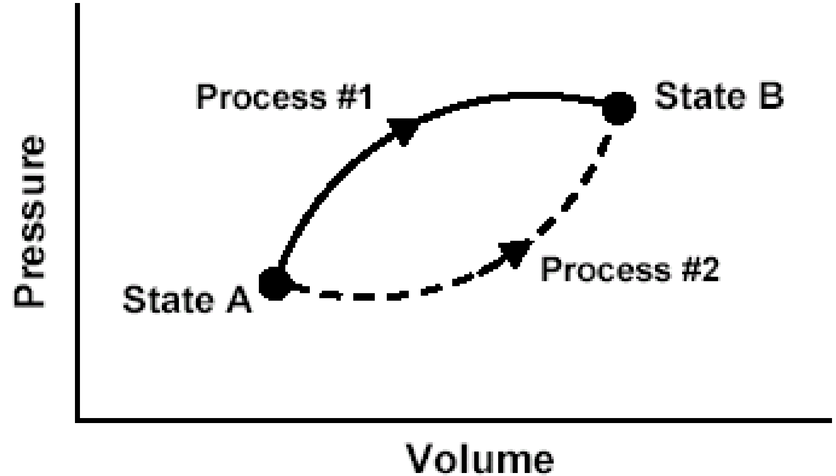

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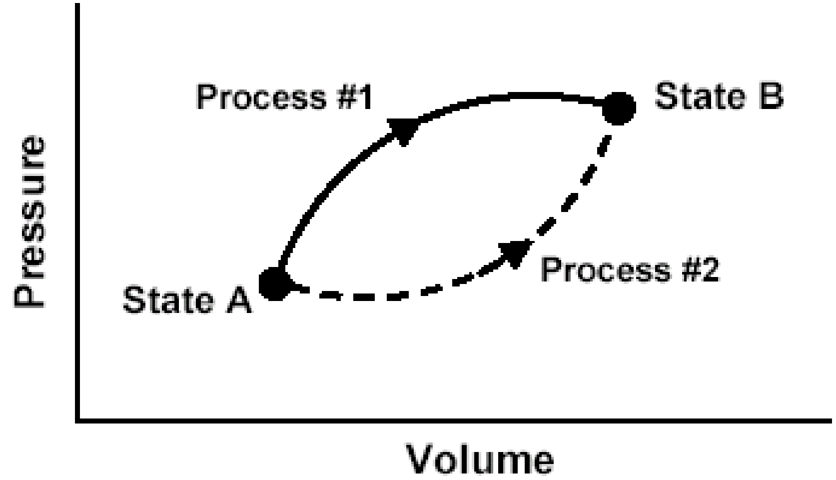
Change in internal energy is the same for Process #1 and Process #2.



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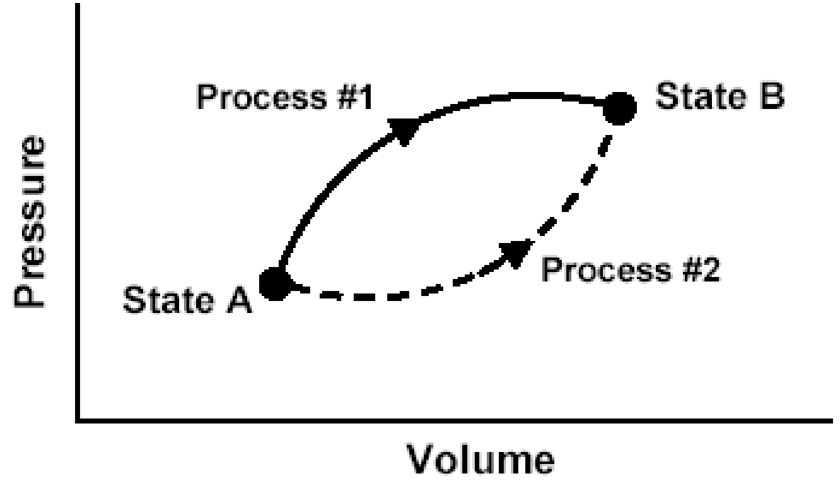
The system does more work in Process #1, so it must absorb more heat to reach same final value of internal energy:
$Q_1 > Q_2$



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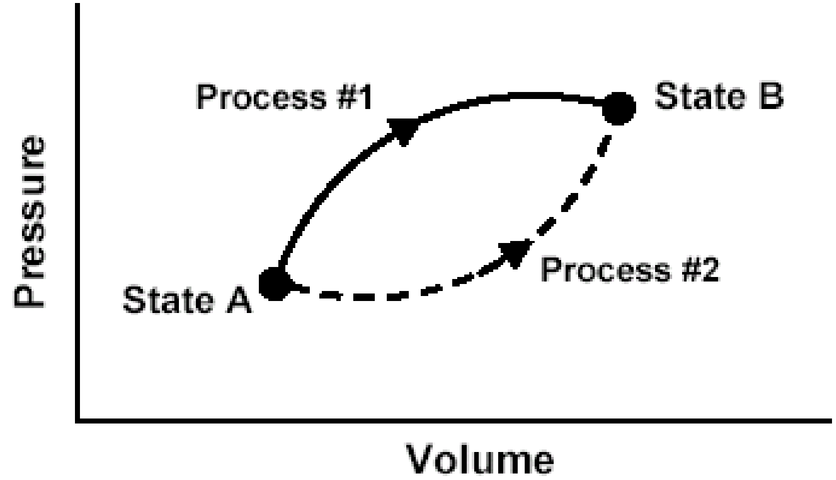

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Responses to Diagnostic Question #2
(Heat question)

	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002 Interview Sample** (*N*=32)
$Q_1 > Q_2$				
$Q_1 = Q_2$				
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Because heat is independent of path	**21%**	**23%**	**20%**	**44%**
Other explanation, or none	**10%**	**18%**	**20%**	**3%**

Explanations Given by Interview Subjects to Justify $Q_1 = Q_2$

- "*I believe that heat transfer is like energy in the fact that it is a state function and doesn't matter the path since they end at the same point*."

- "*Transfer of heat doesn't matter on the path you take*."

- "*They both end up at the same PV value so . . . They both have the same Q or heat transfer*."

➢ **Almost 150 students offered arguments similar to these either in their written responses or during the interviews.**

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Predominant Themes of Students' Reasoning

1. Understanding of concept of state function in the context of energy.
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Research Basis for Curriculum Development

(NSF CCLI Project with T. Greenbowe)

- Investigation of second-semester calculus-based physics course (mostly engineering students).
- Written diagnostic questions administered last week of class in 1999, 2000, and 2001 (N_{total} = 653).
- Detailed interviews (avg. duration ≥ one hour) carried out with 32 volunteers during 2002 (total class enrollment: 424).
  - *interviews carried out after all thermodynamics instruction completed*
  - *final grades of interview sample far above class average*

Interview Questions

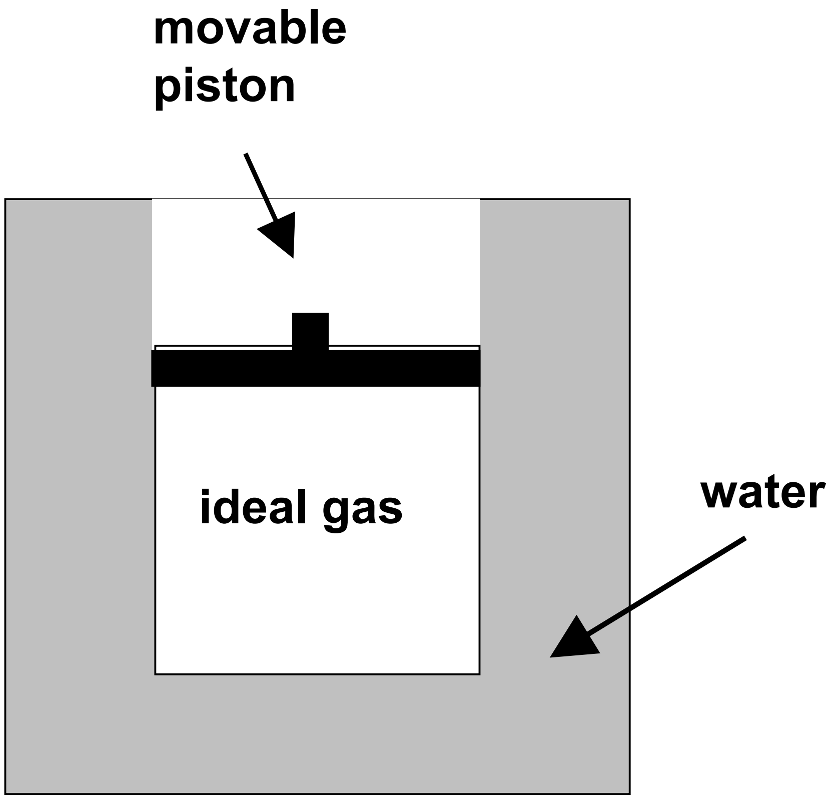
A fixed quantity of ideal gas is contained within a metal cylinder that is sealed with a movable, frictionless, insulating piston.

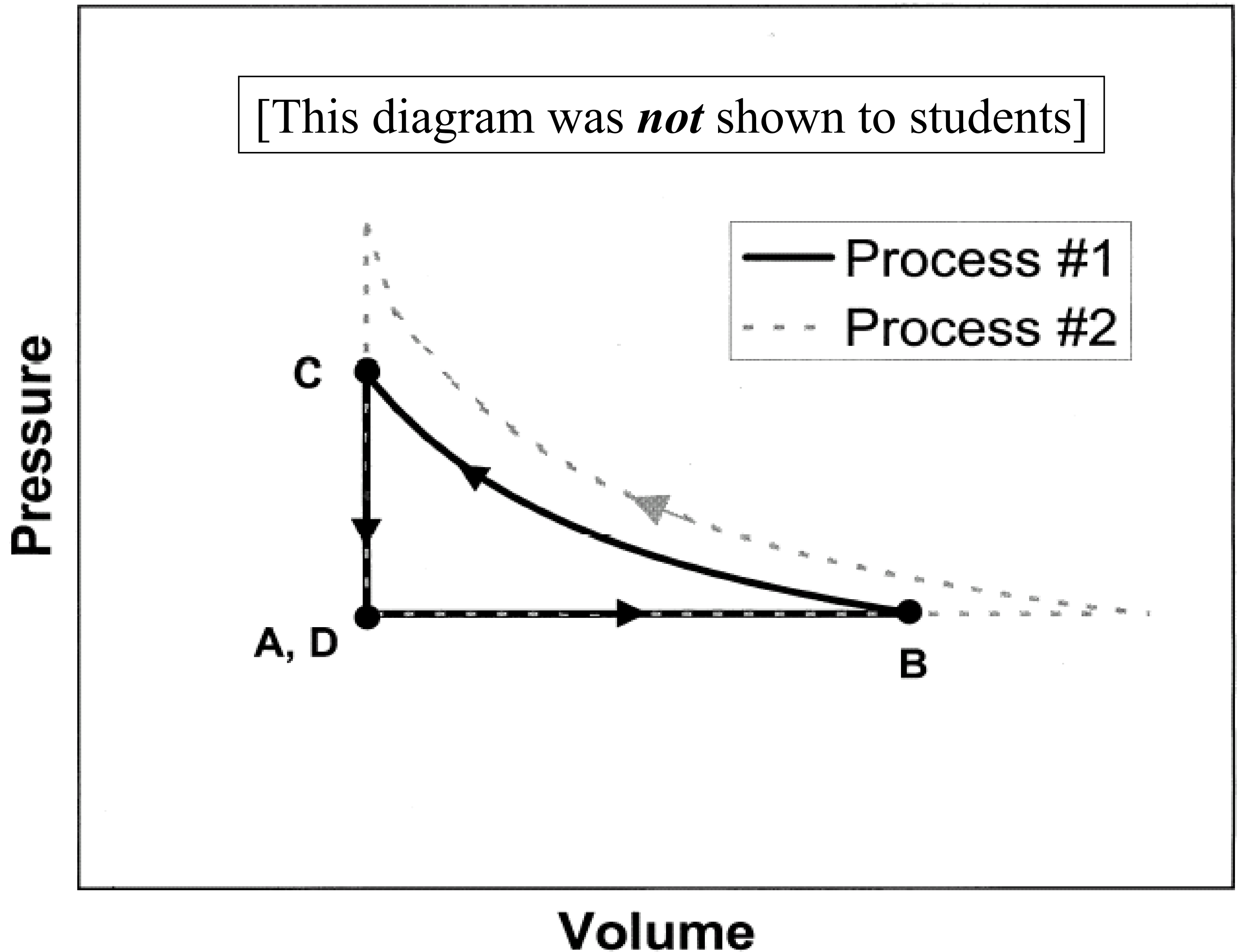
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

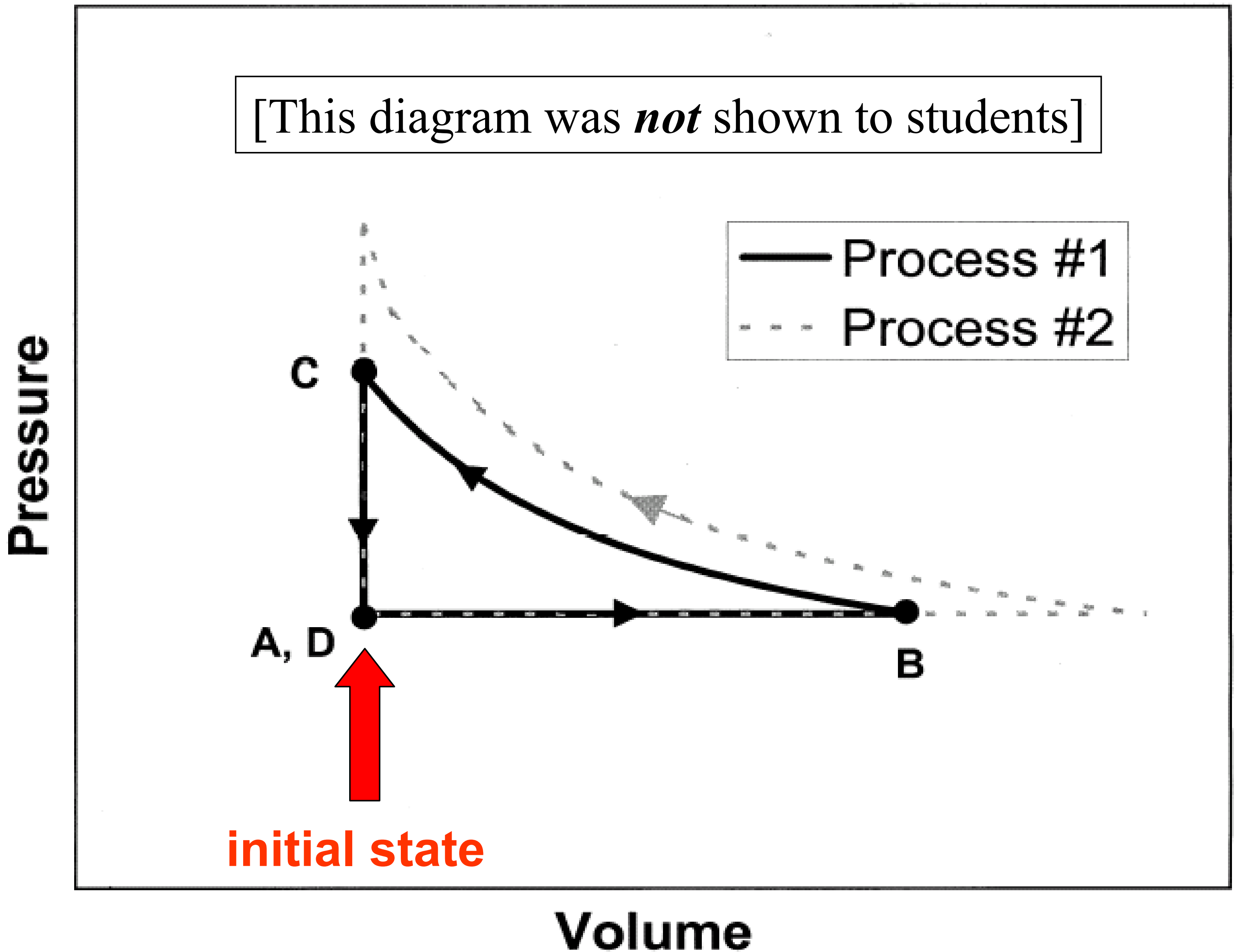
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature

Time *A*

Entire system at room temperature.

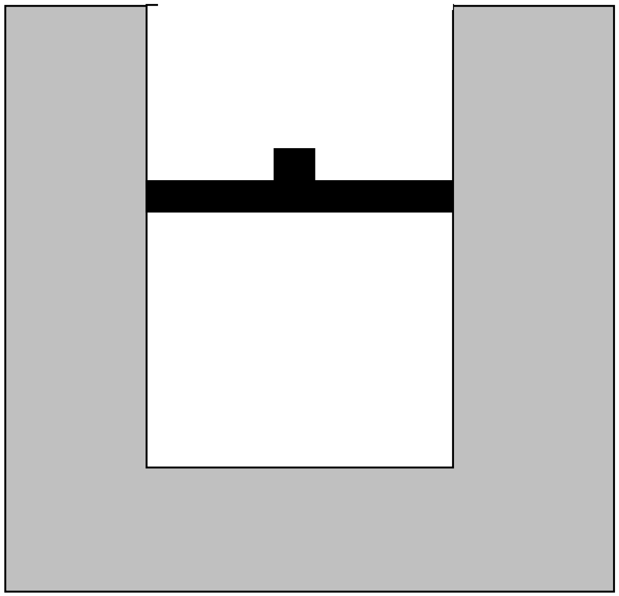


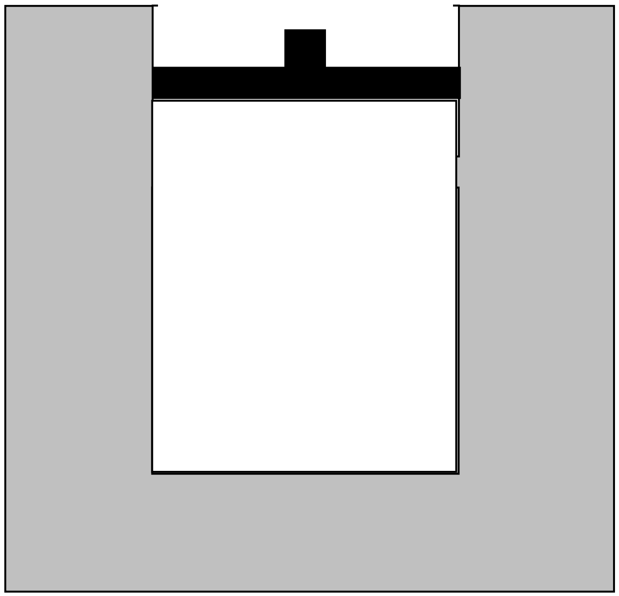

[This diagram was not shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



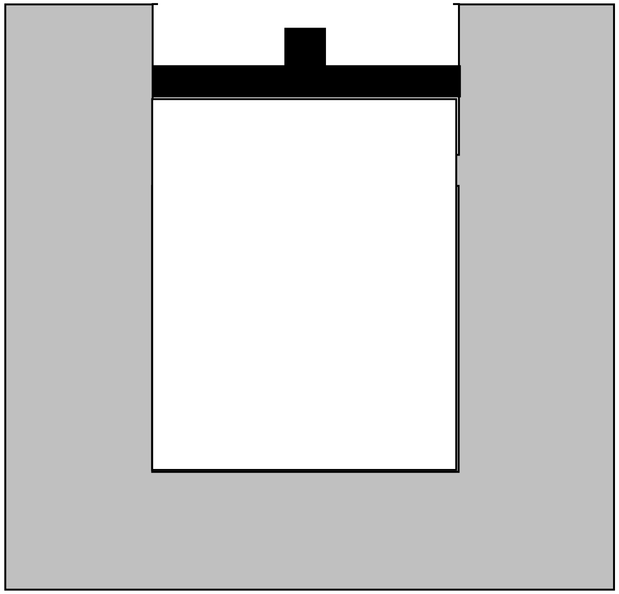
[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
initial state
Pressure
Volume

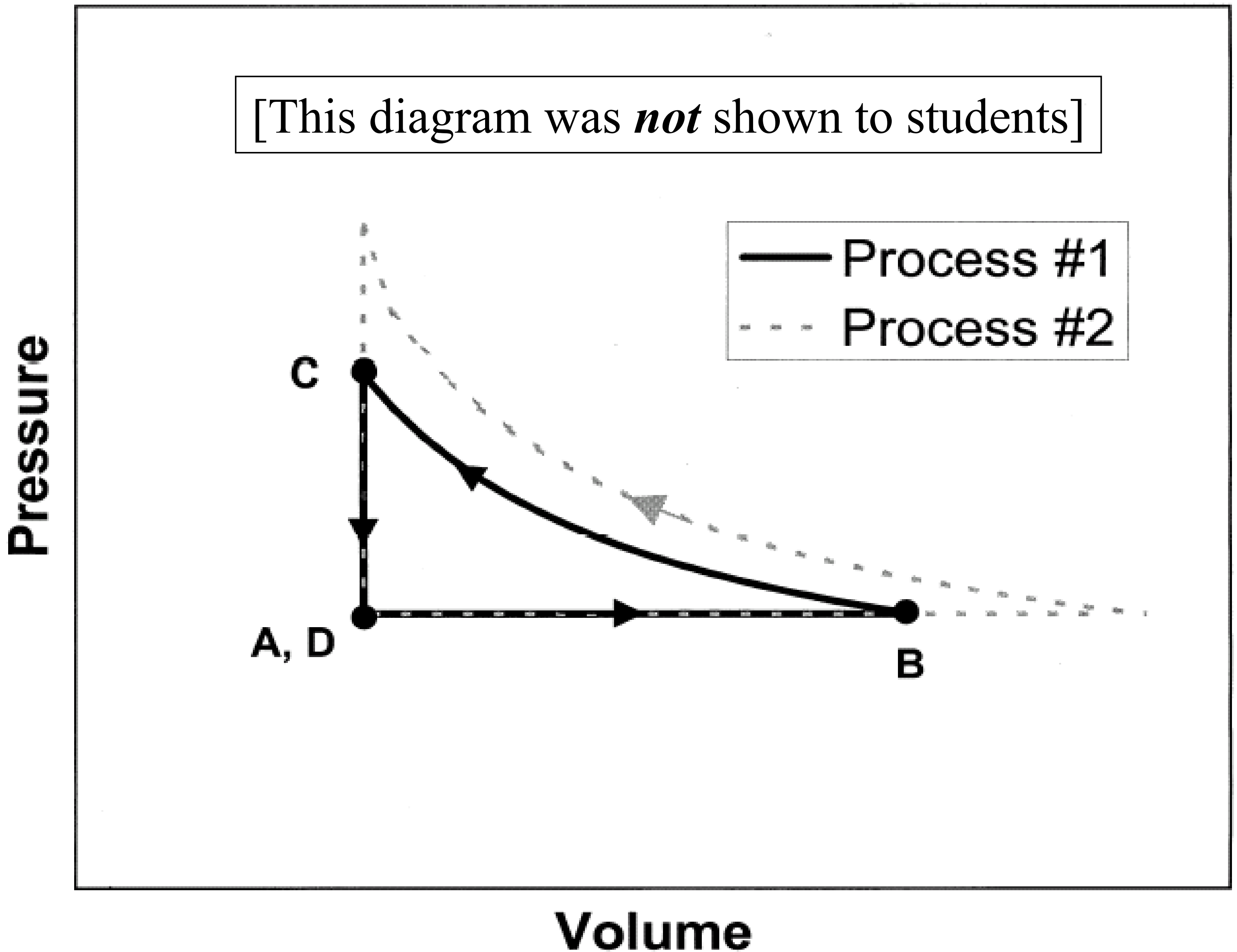
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.





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

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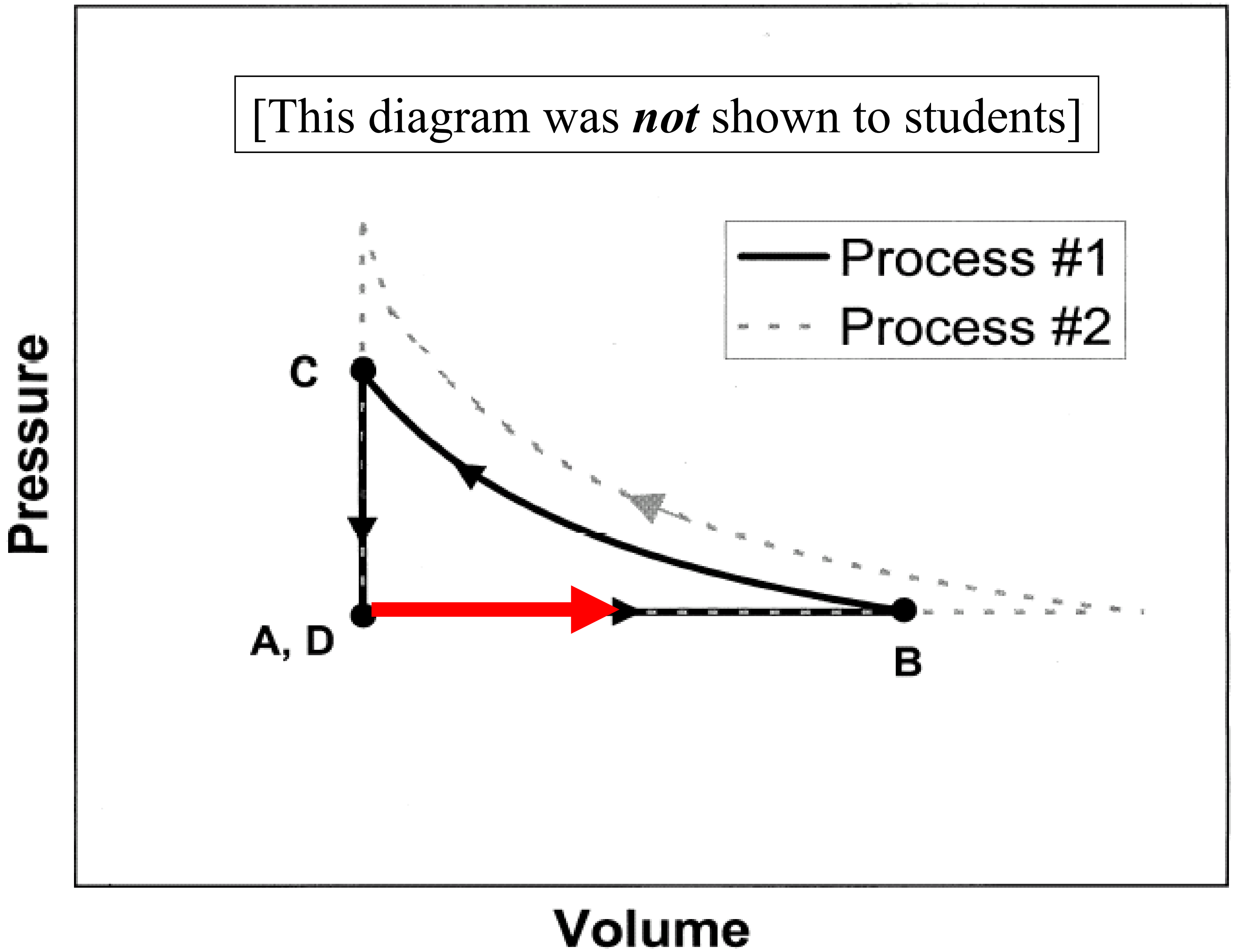
Process #1
Process #2
C
A, D
B
Pressure
Volume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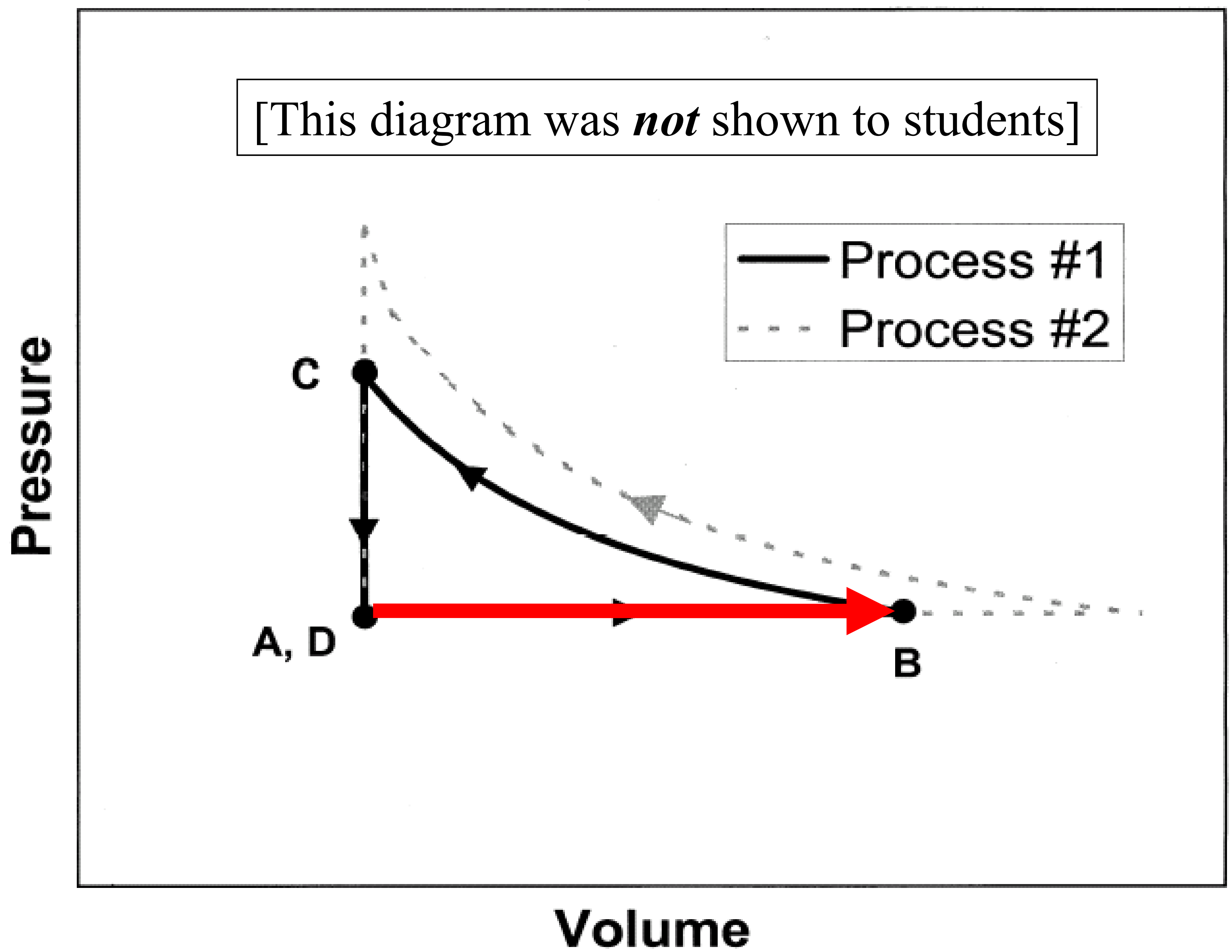
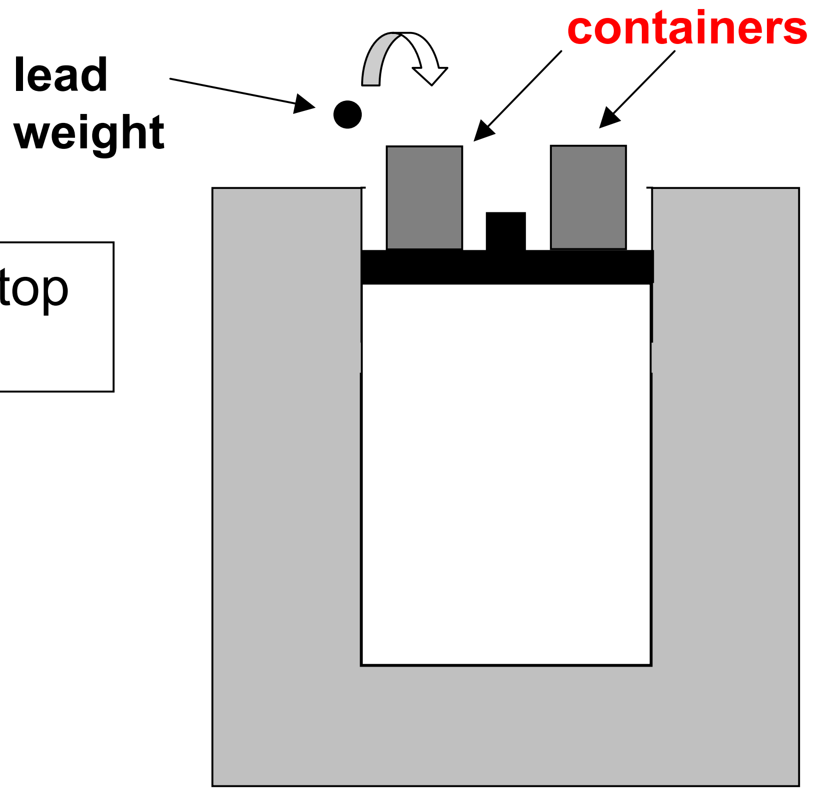
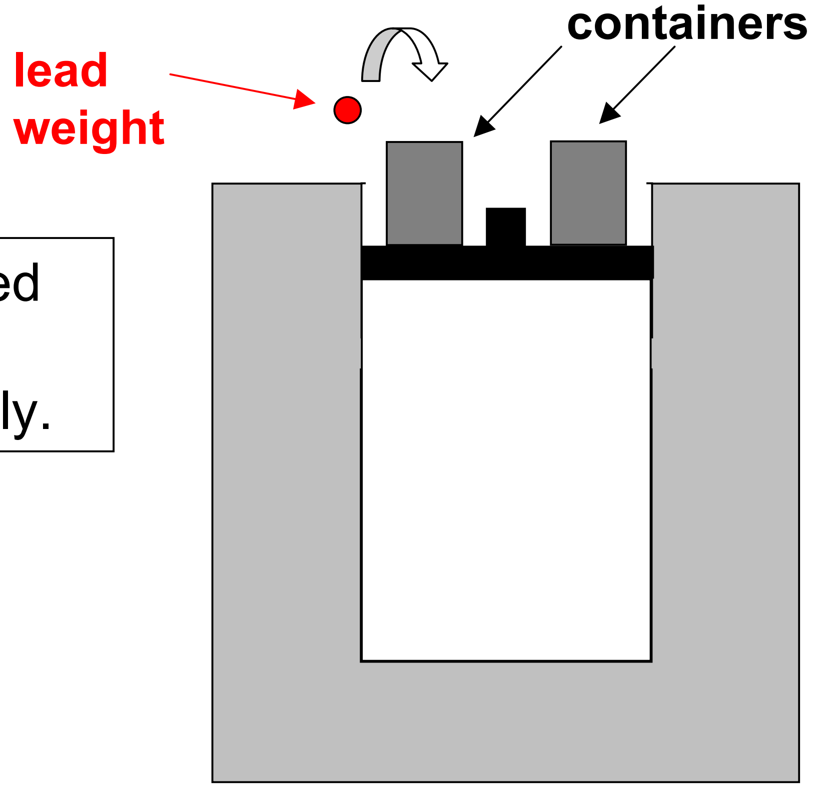
Process #1
Process #2
C
A, D
B
Pressure
Volume

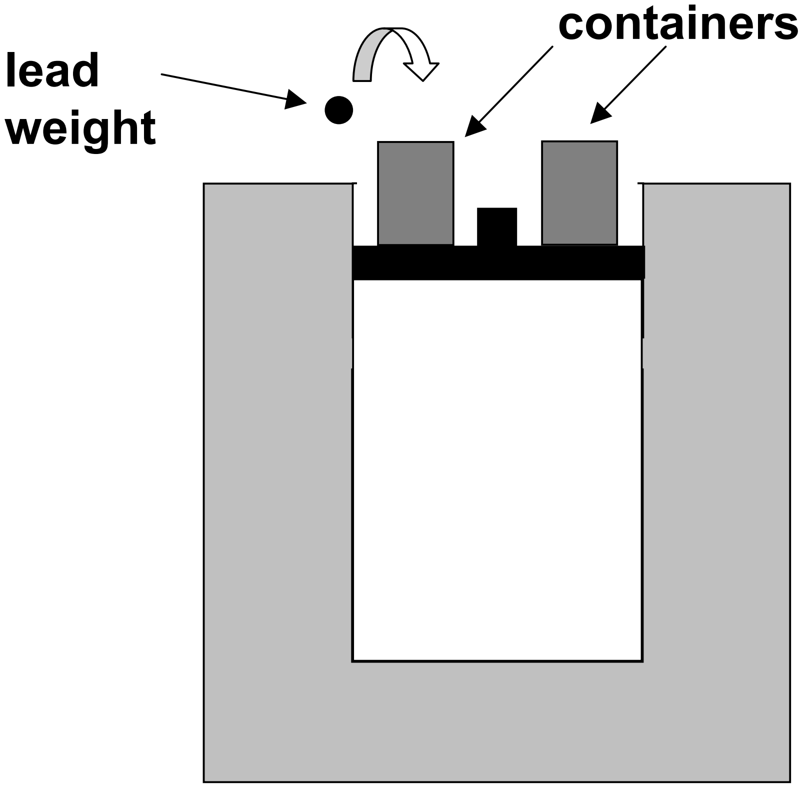

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

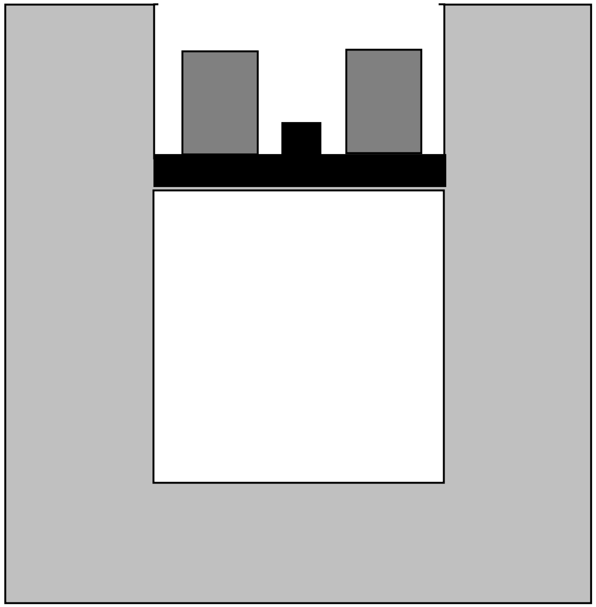
Now, empty containers are placed on top of the piston as shown.



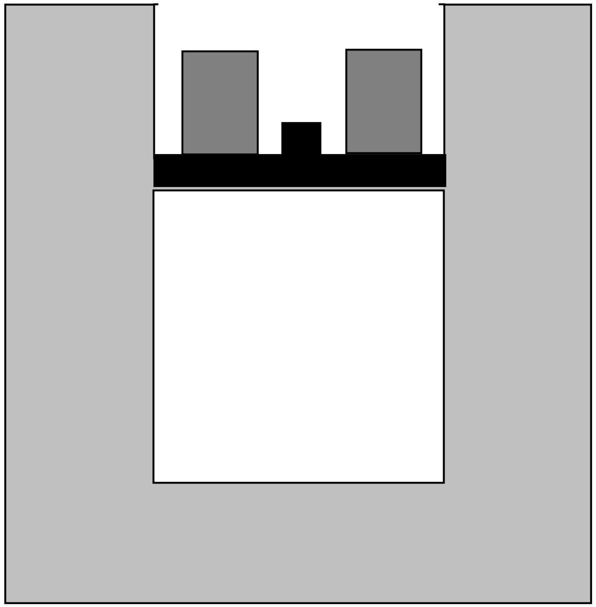
Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly.



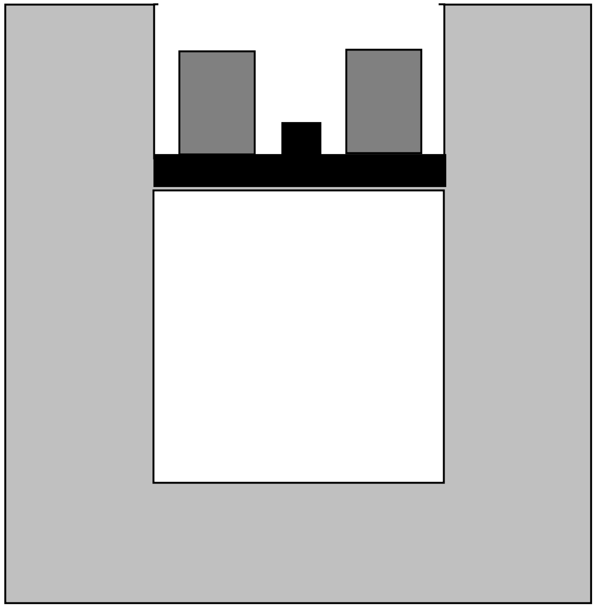

lead
weight
containers

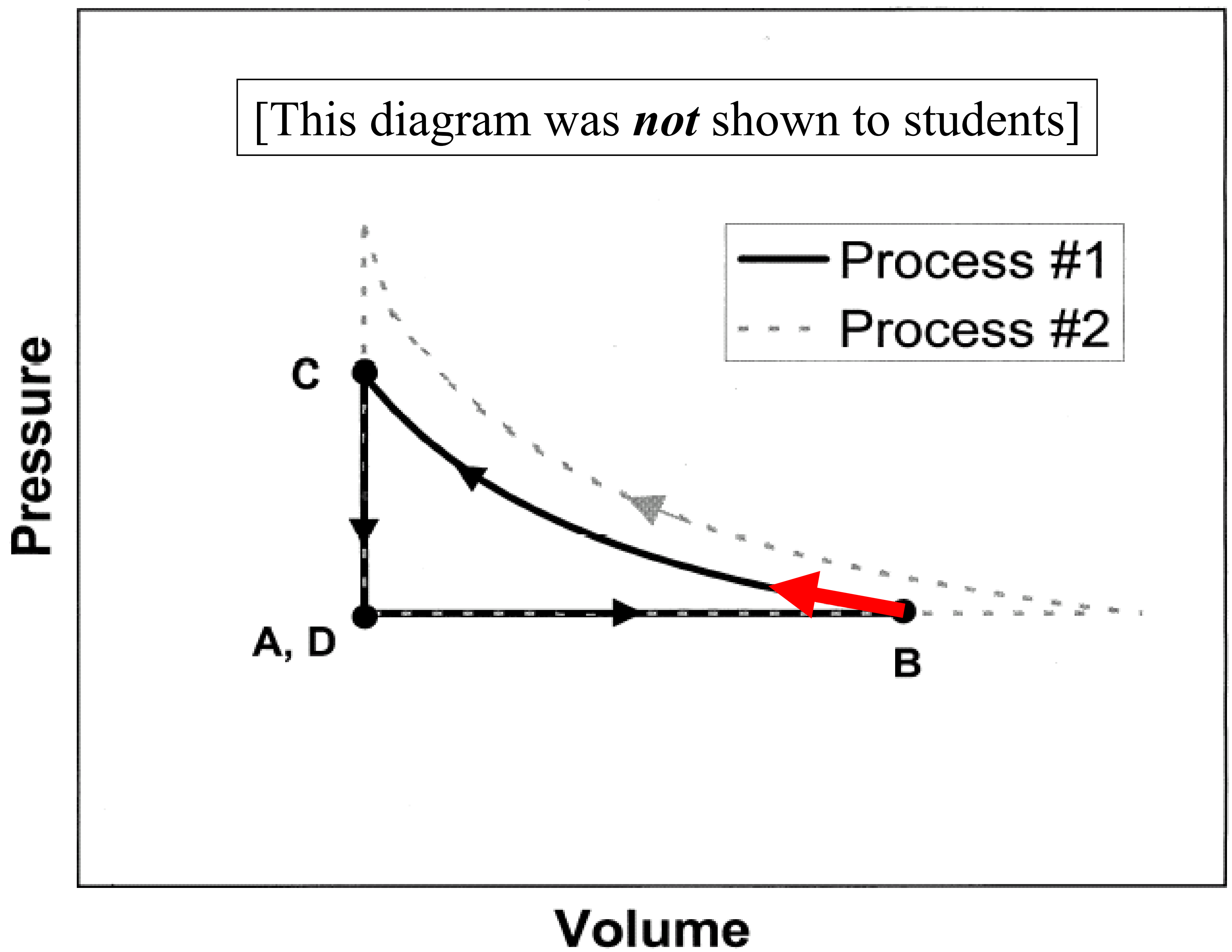


While this happens the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*.



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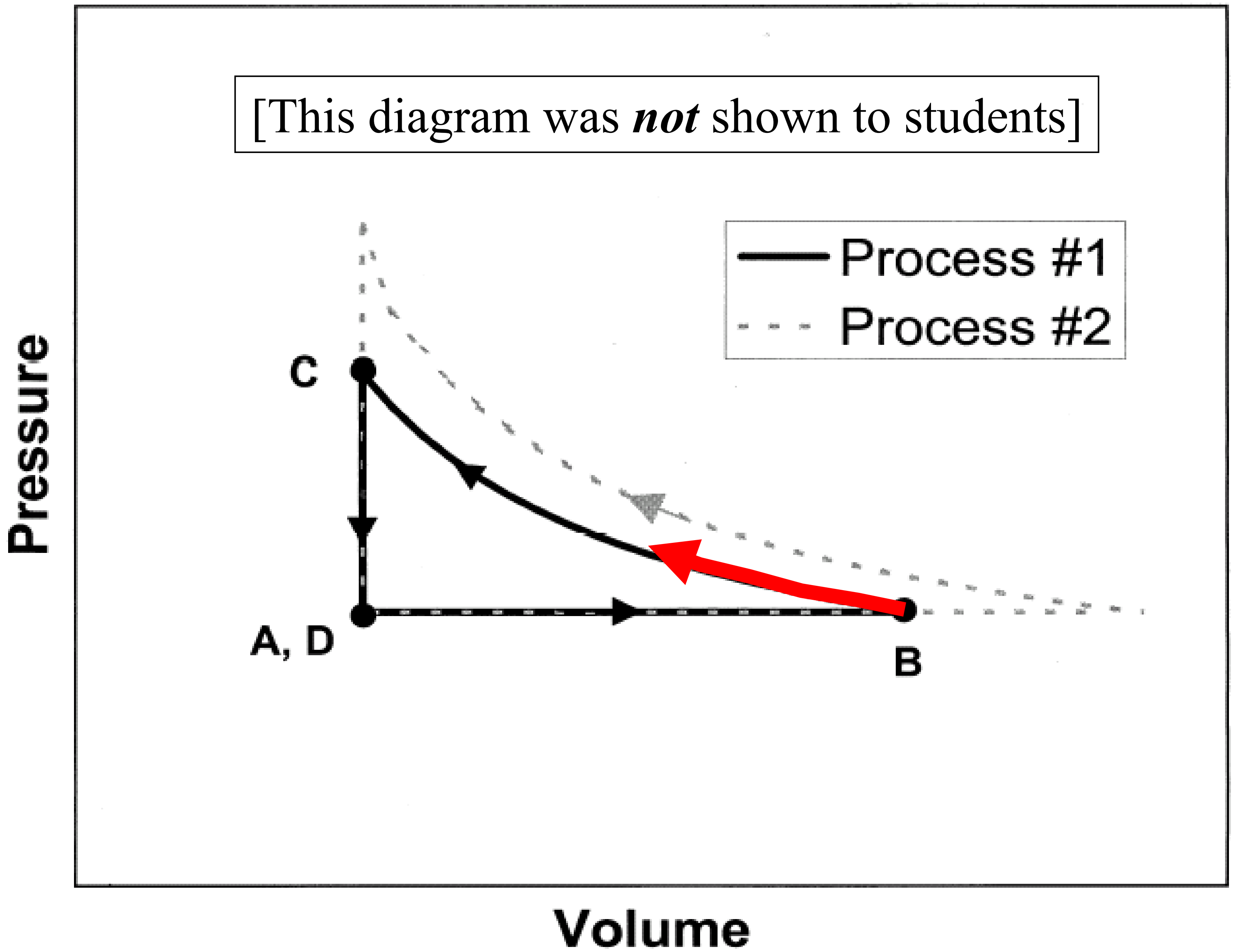
Process #1
Process #2
C
A, D
B
Pressure
Volume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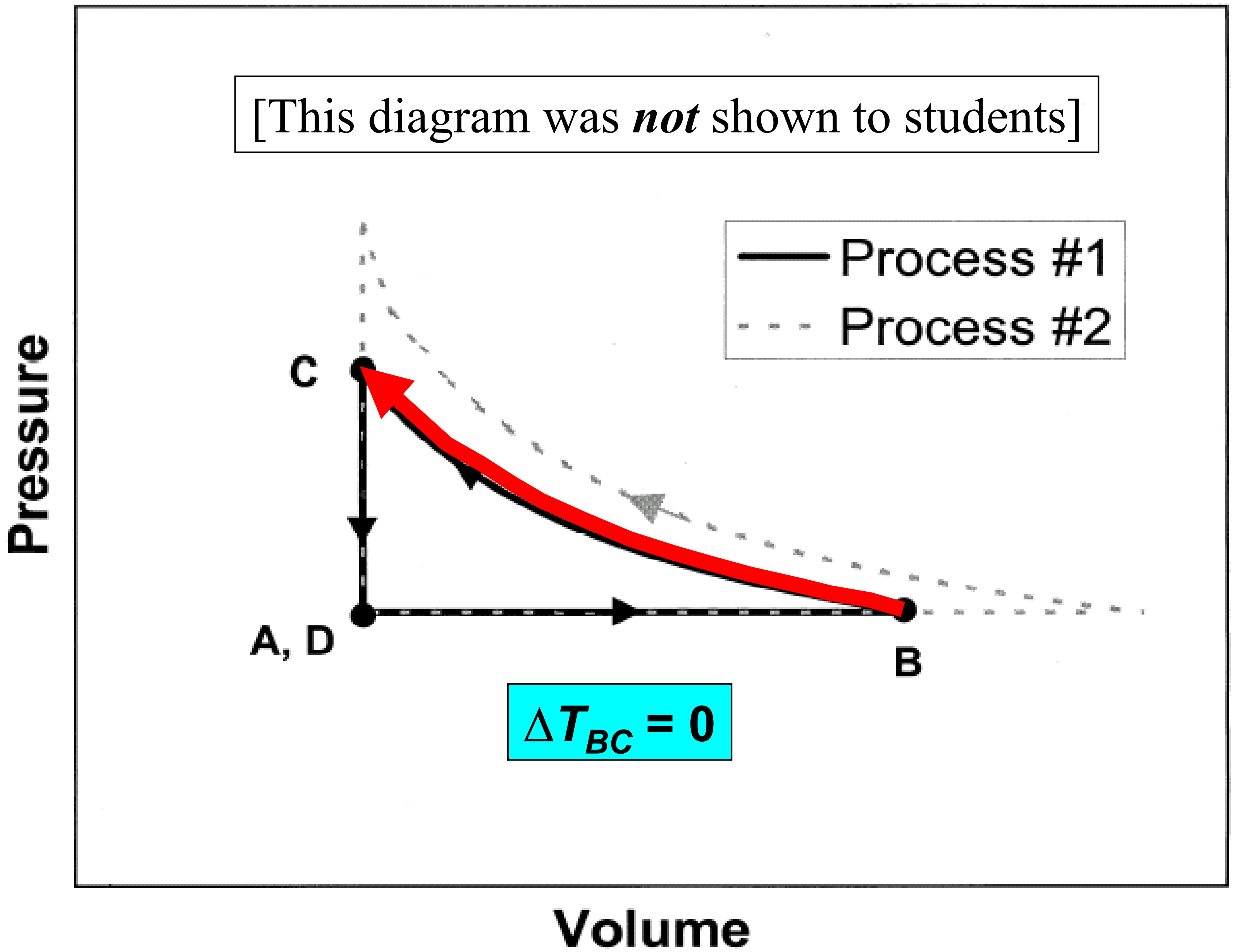
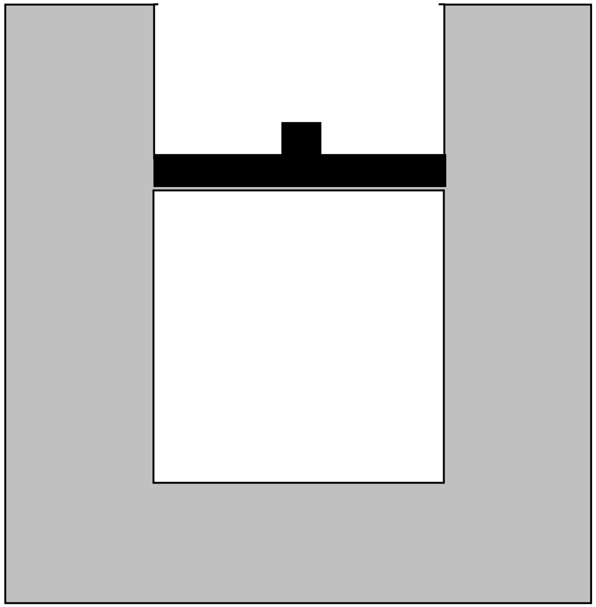
Process #1
Process #2
C
A, D
B
Pressure
Volume

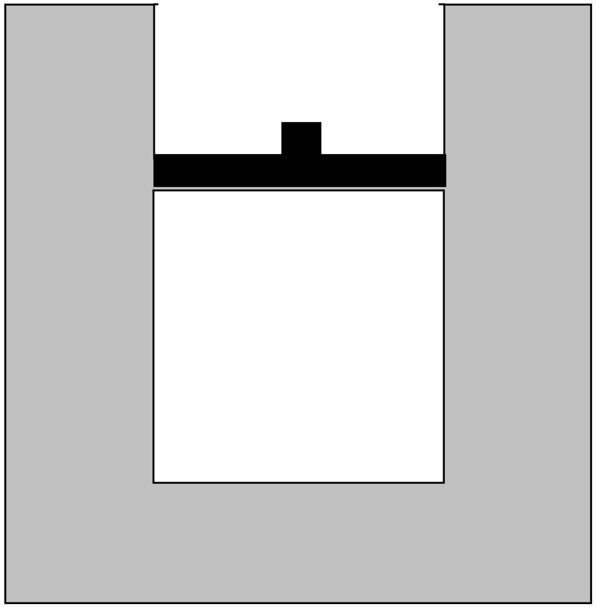


[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
$\Delta T_{BC} = 0$
Pressure
Volume

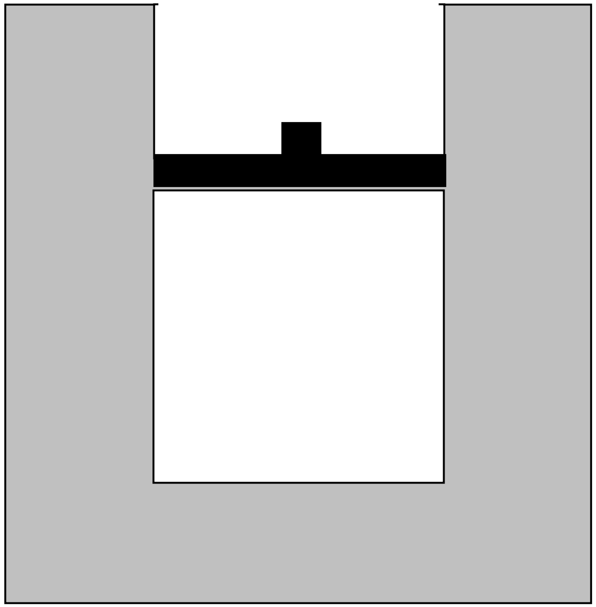
Now, the piston is locked into place so it *cannot move*, and the weights are removed from the piston.



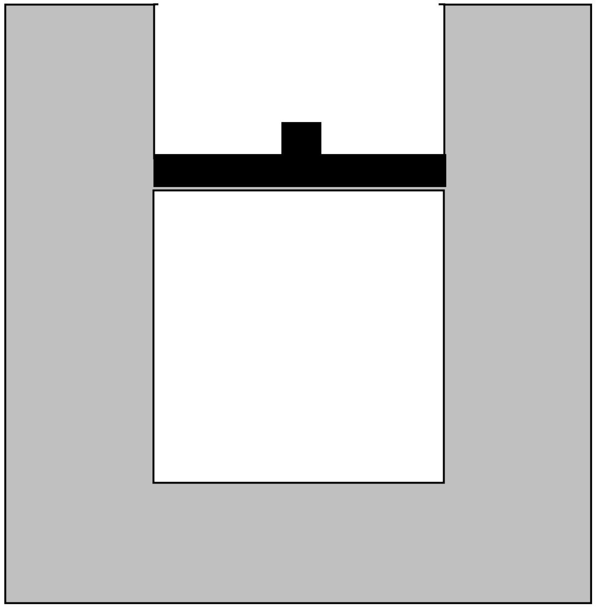
The system is left to sit in the room for many hours.



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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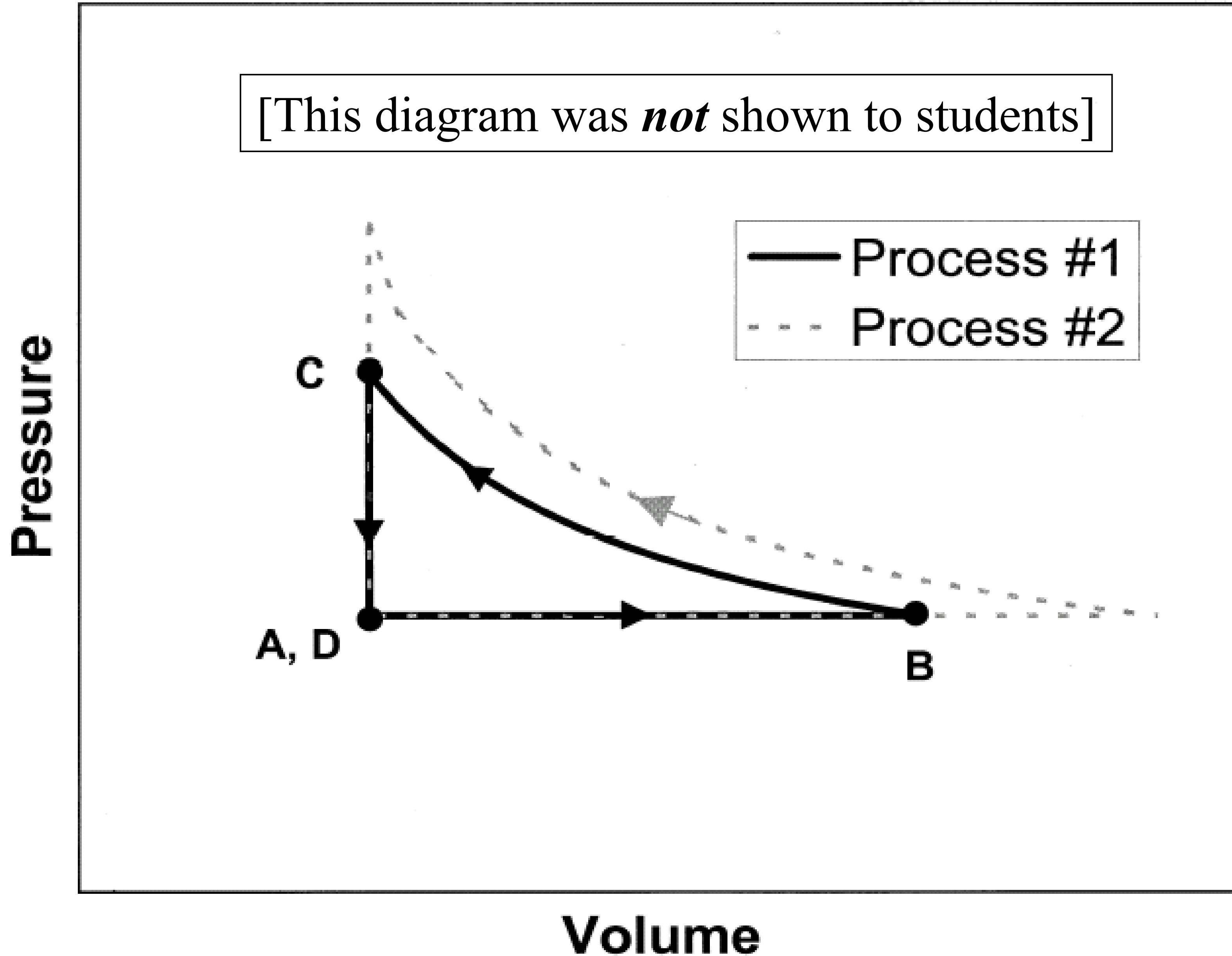

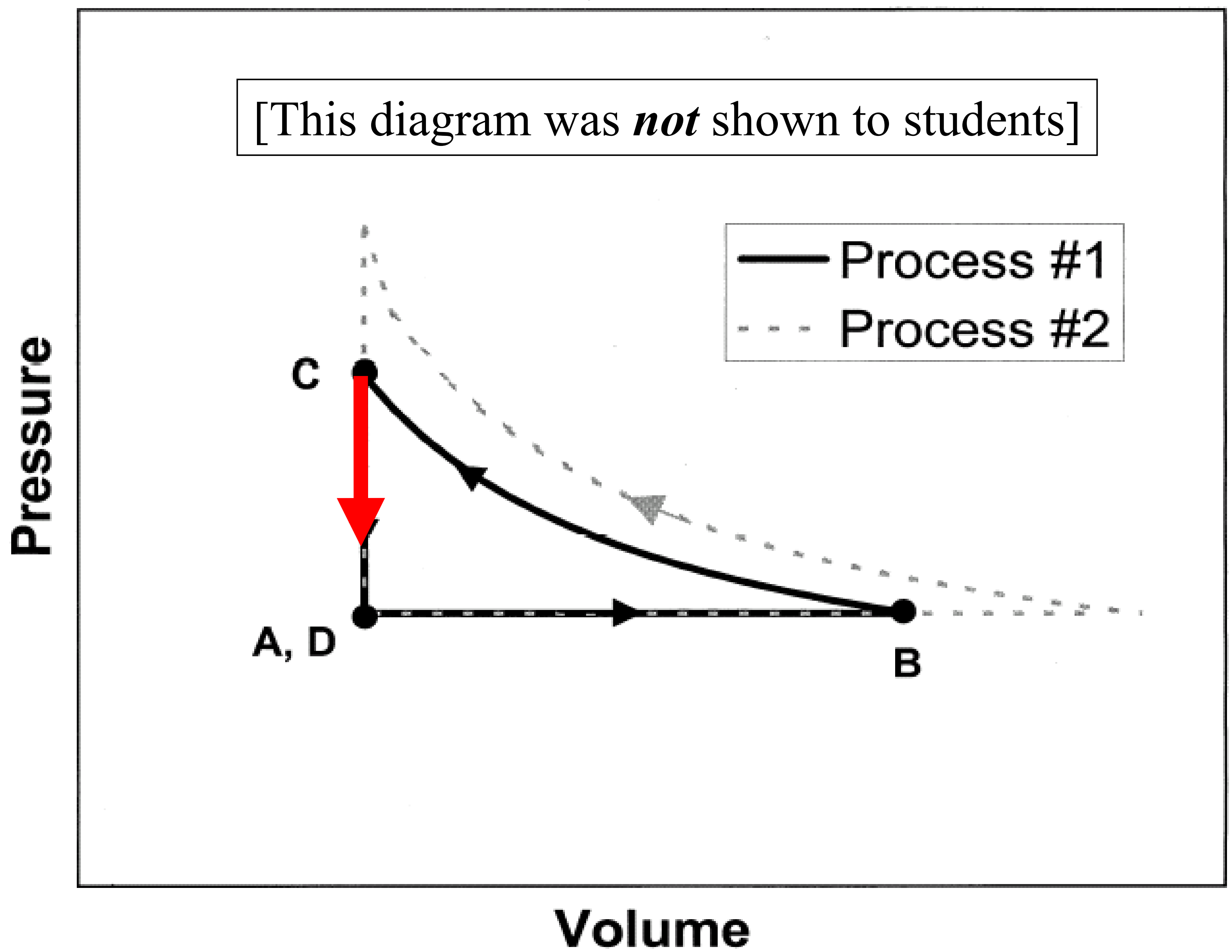
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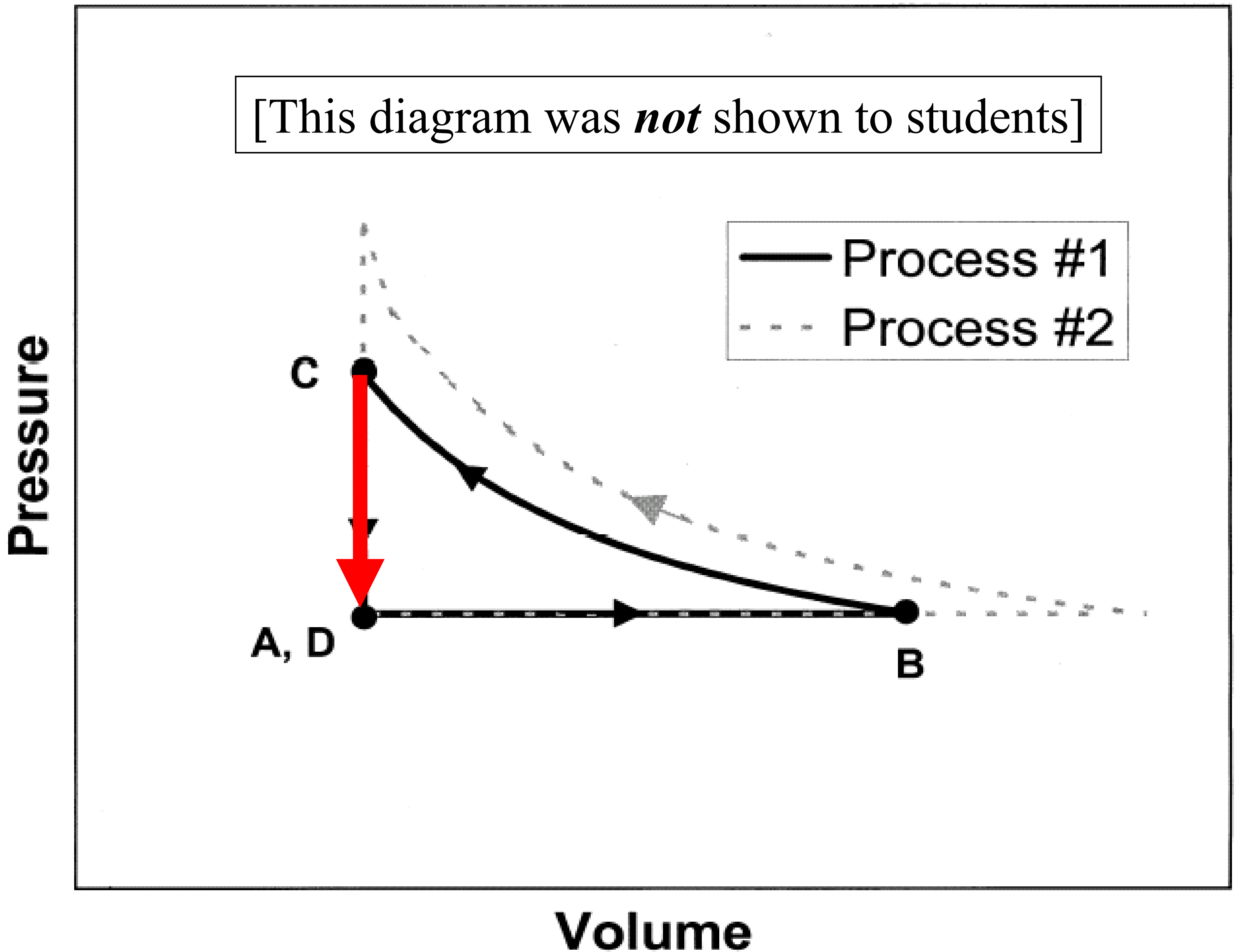
Process #1
Process #2
Pressure
C
A, D
B
Volume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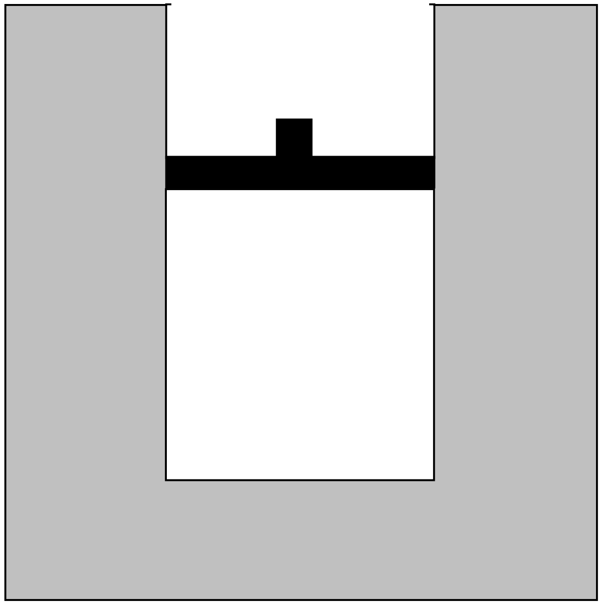
Process #1
Process #2
C
A, D
B
Pressure
Volume



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

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

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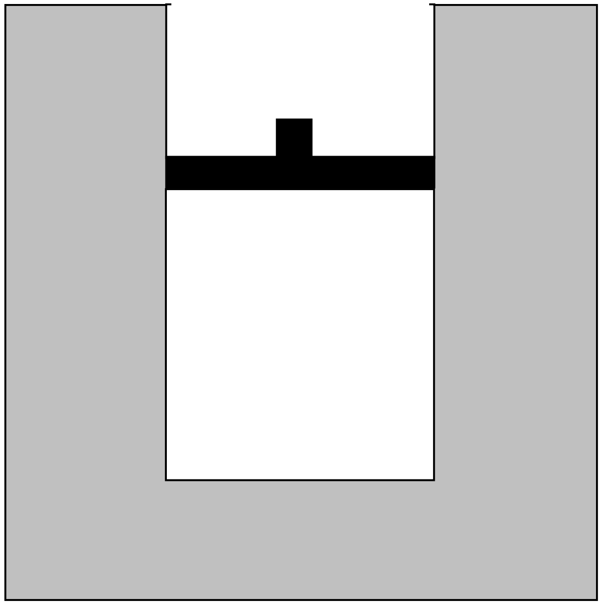

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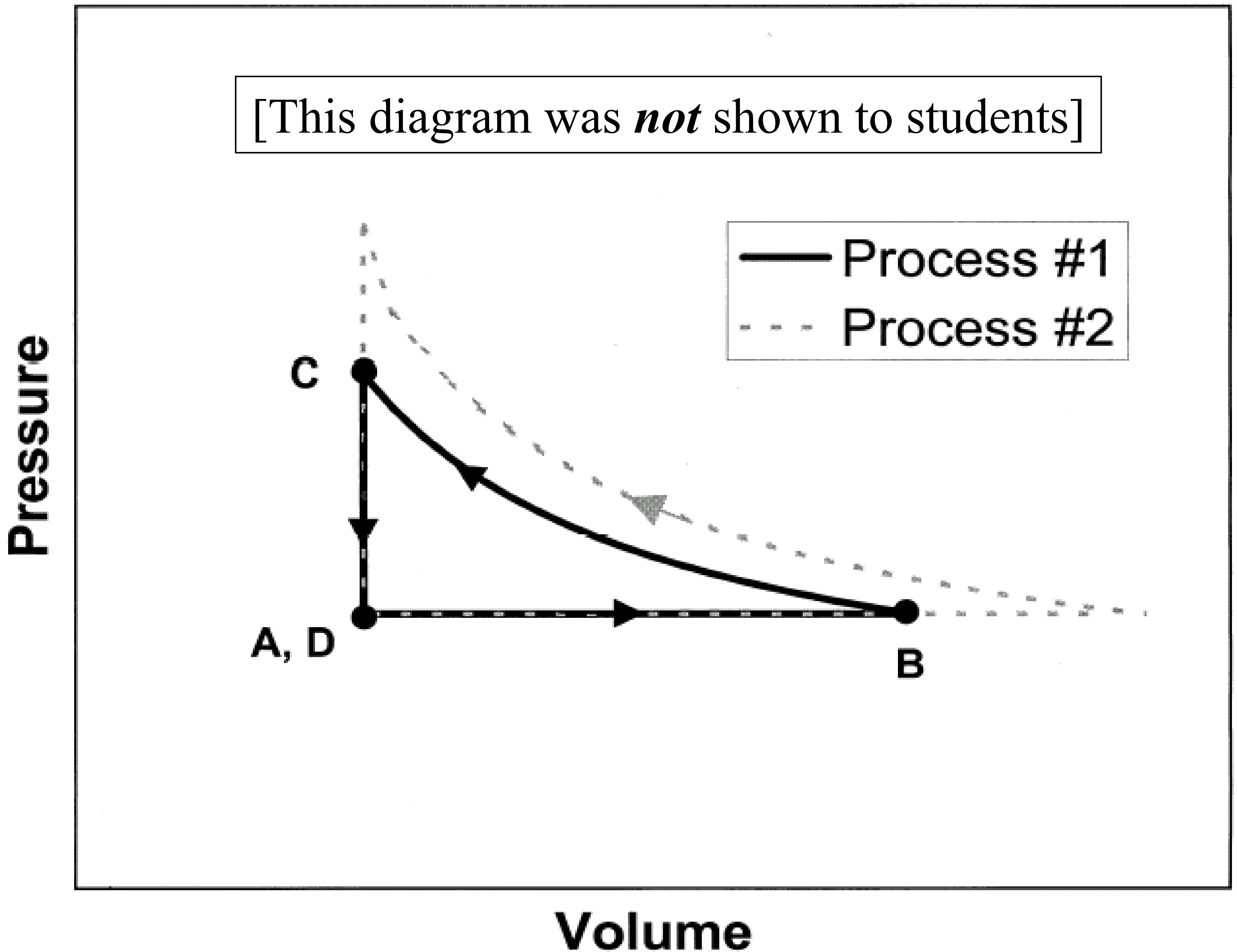
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Process #2
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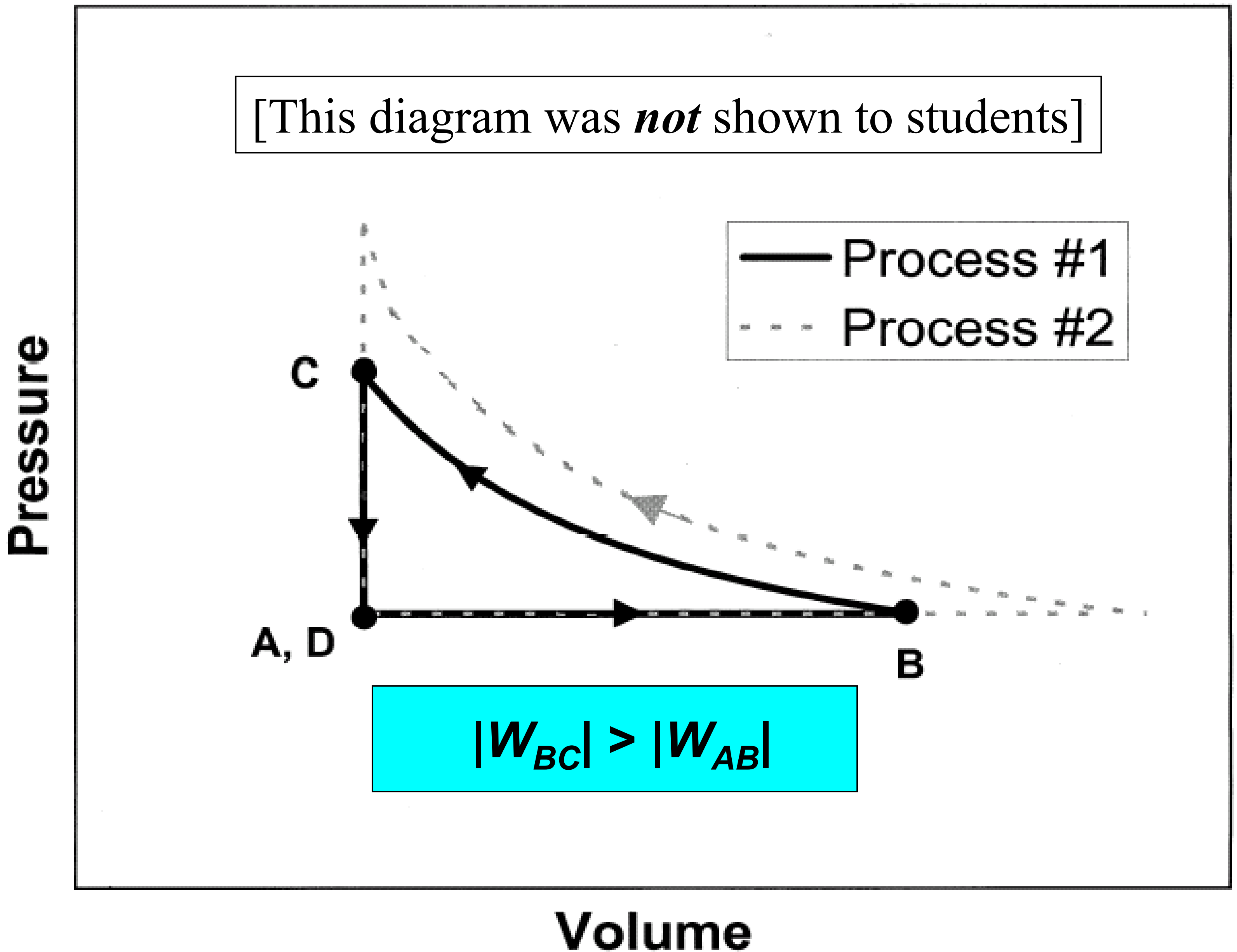
A, D
B
Pressure
Volume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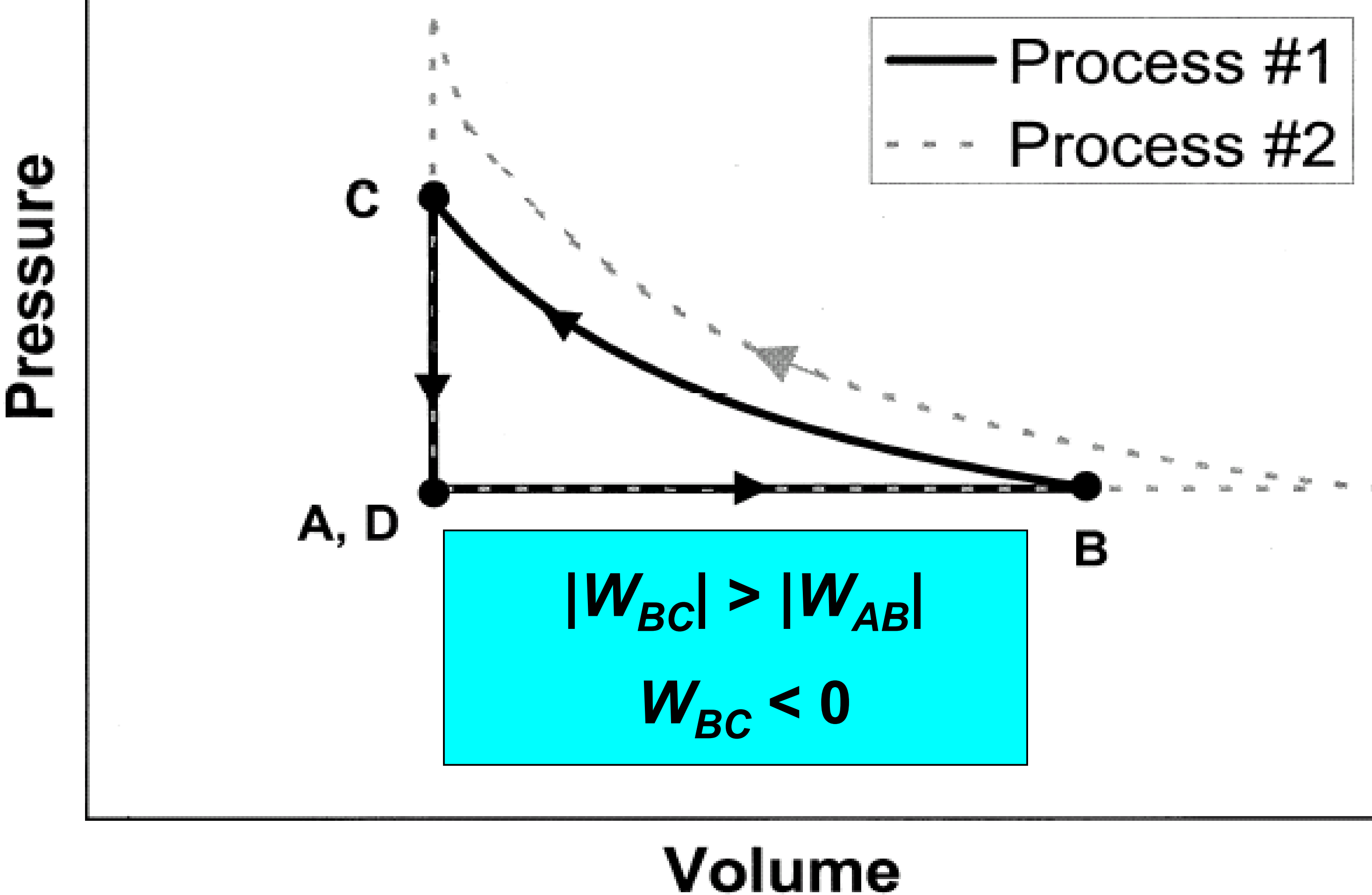
Process #1
Process #2
C
A, D
B
Pressure
Volume
$|W_{BC}| > |W_{AB}|$

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



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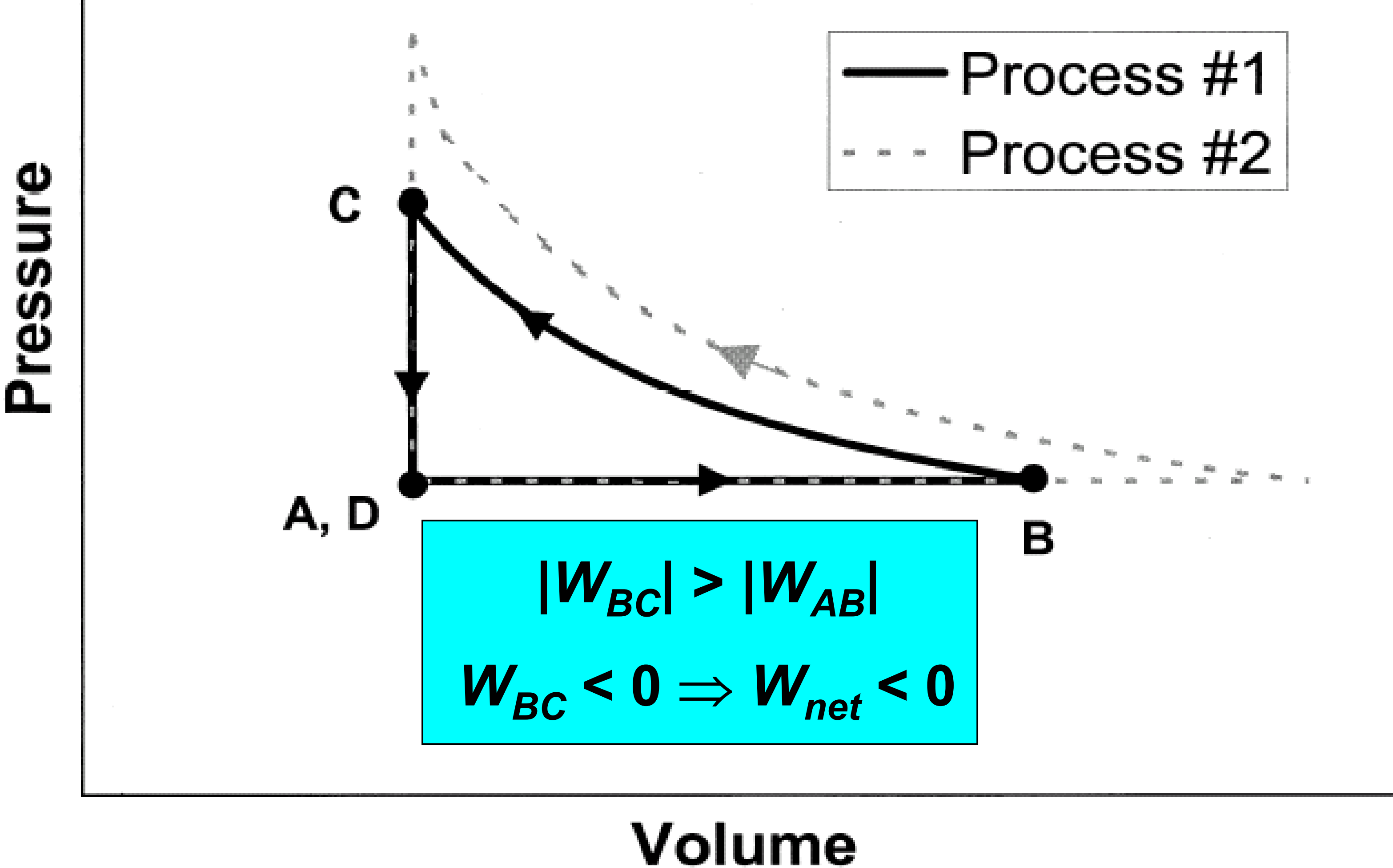
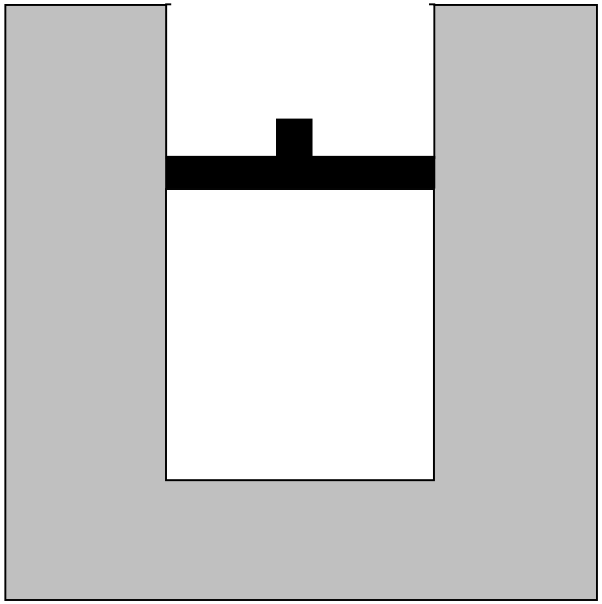


$$|W_{BC}| > |W_{AB}|$$

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



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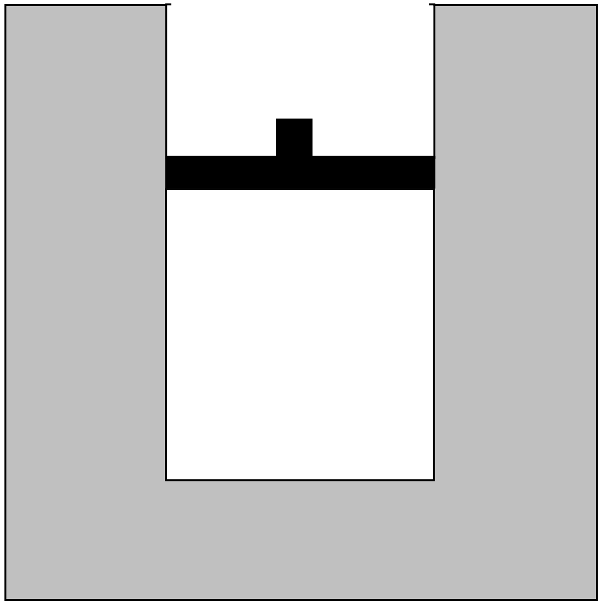

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Results on Interview Question #6 (i)

N = 32

(a) $W_{net} > 0$: 16%

(b) $W_{net} = 0$: 63%

(c) $W_{net} < 0$: 19% ***[correct]***

No response: 3%

Nearly two thirds of the interview sample believed that net work done was equal to zero.

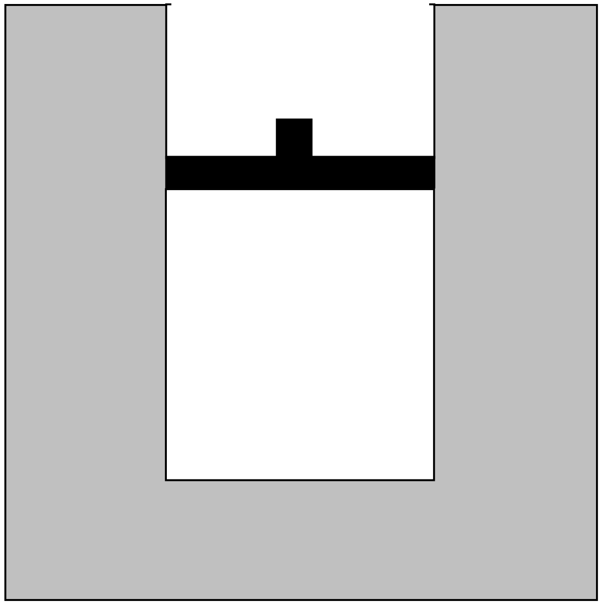
Explanations offered for $W_{net} = 0$

"[Student #1:] *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*."

Explanations offered for $W_{net} = 0$

"[Student #1:] *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*."

"[Student #2:] *At one point the volume increased and then the pressure increased, but it was returned back to that state . . . The piston went up so far and then it's returned back to its original position, retracing that exact same distance*."



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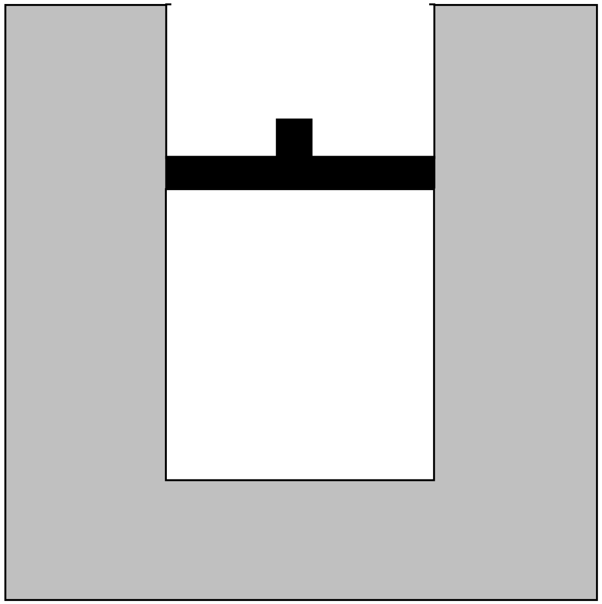

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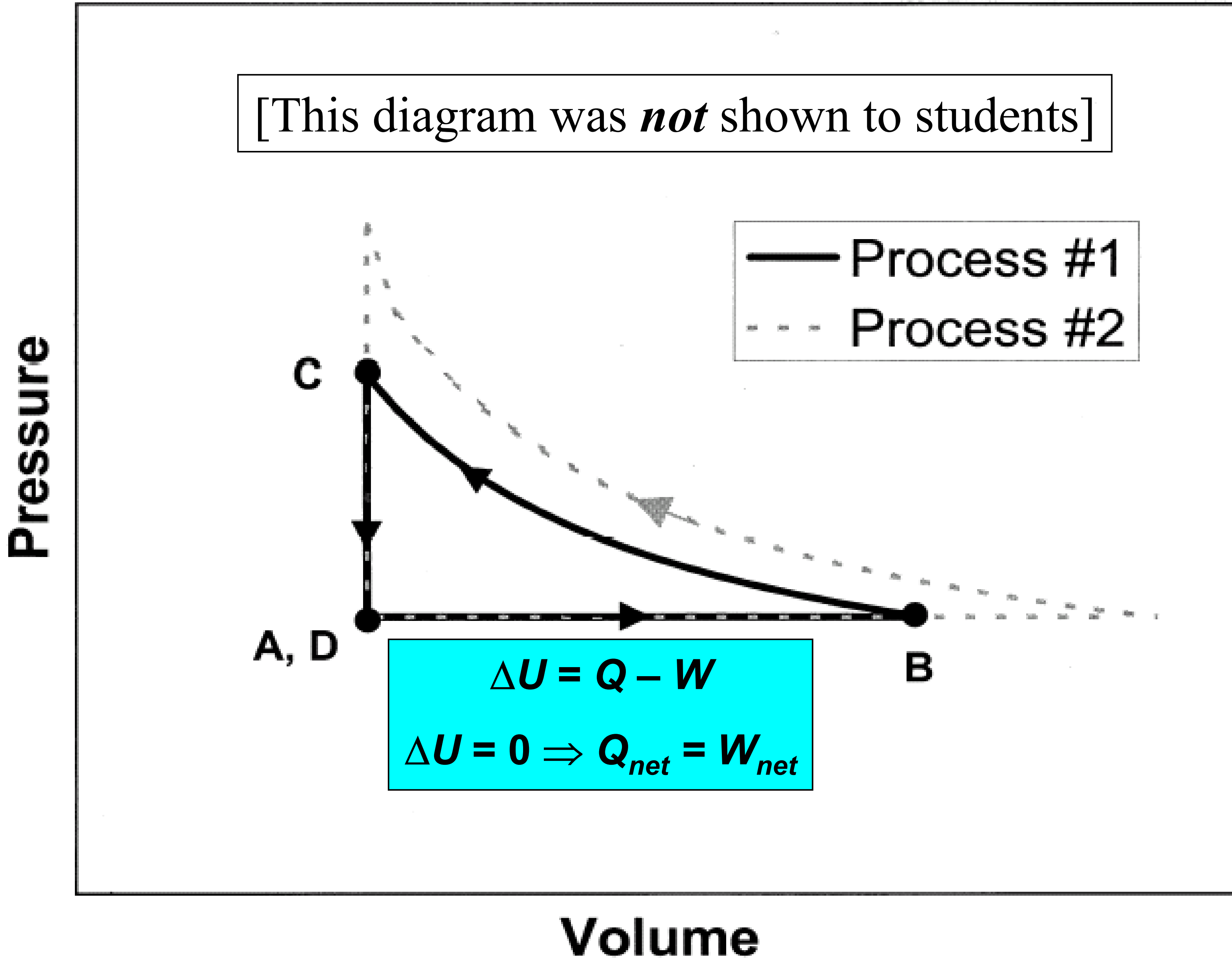
[This diagram was ***not*** shown to students]



$$\Delta U = Q - W$$

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

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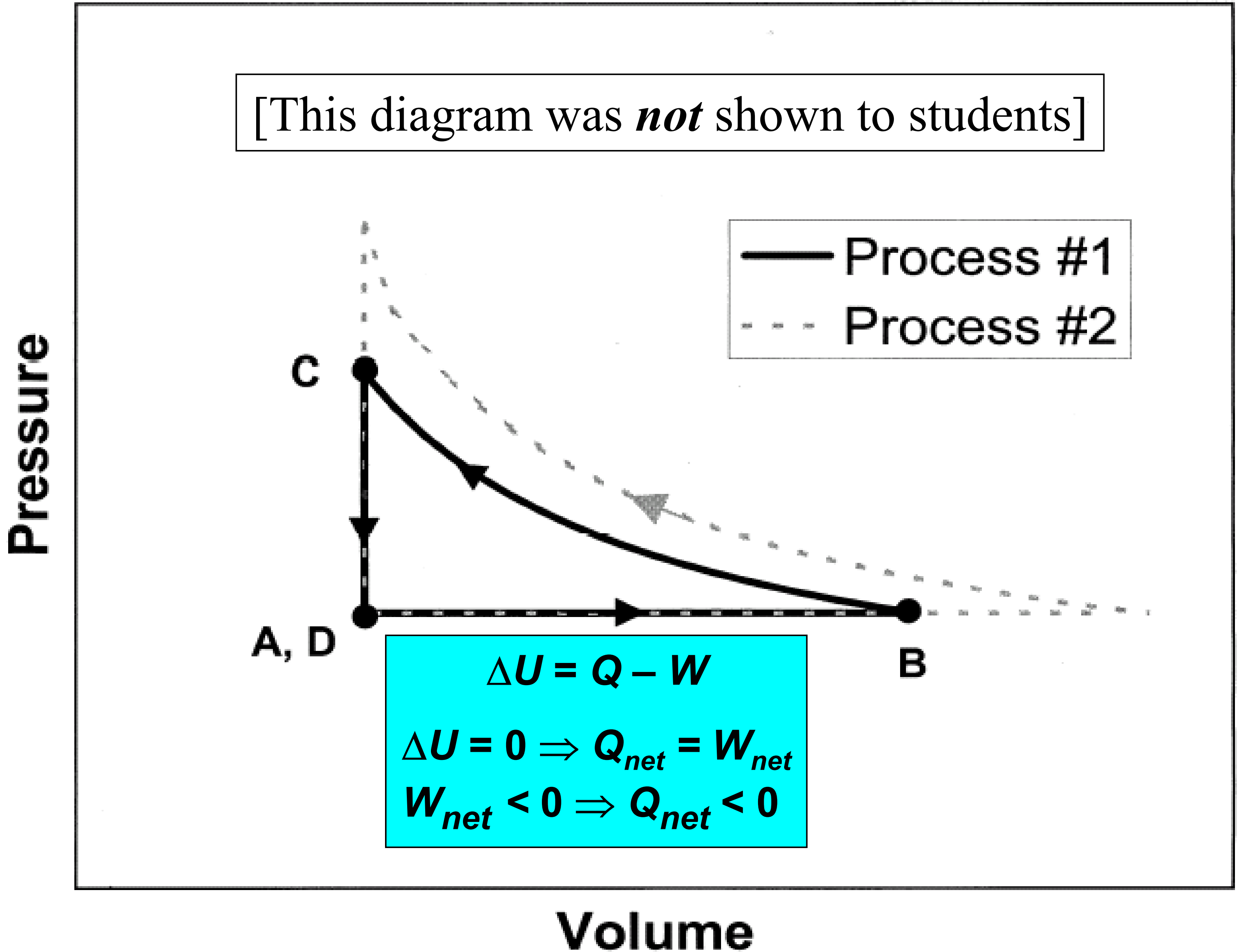
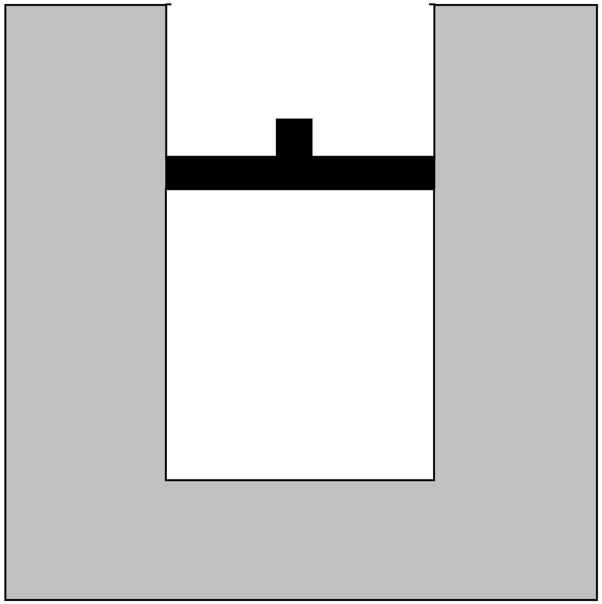


$$\Delta U = Q - W$$

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

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



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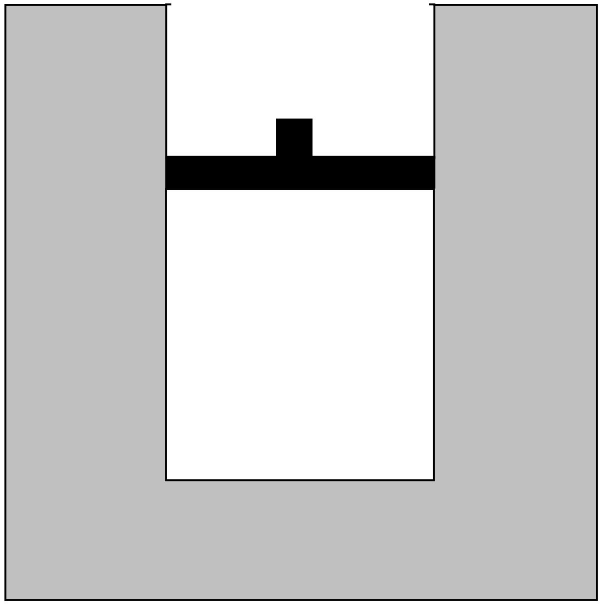

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Results on Interview Question #6 (ii)

$N = 32$

(a) $Q_{net} > 0$	**9%**	
(b) $Q_{net} = 0$	**69%**	
(c) $Q_{net} < 0$	**16%**	***[correct]***

with correct explanation: ***13%***

with incorrect explanation: ***3%***

Uncertain: **6%**

More than two thirds of the interview sample believed that net heat absorbed was equal to zero.

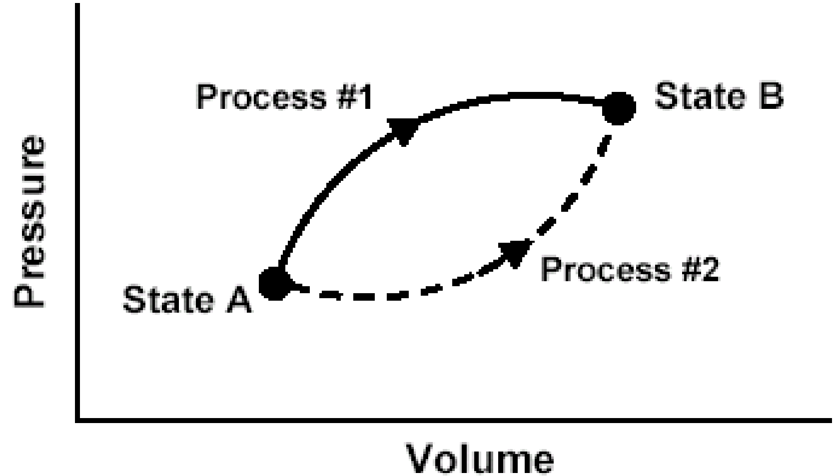
Explanation offered for $Q_{net} = 0$

"*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.*"

Predominant Themes of Students' Reasoning

1. Understanding of concept of state function in the context of energy.
2. Belief that work is a state function.
3. Belief that heat is a state function.
4. Belief that net work done and net heat transferred during a cyclic process are zero.
5. Inability to apply the first law of thermodynamics.

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



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

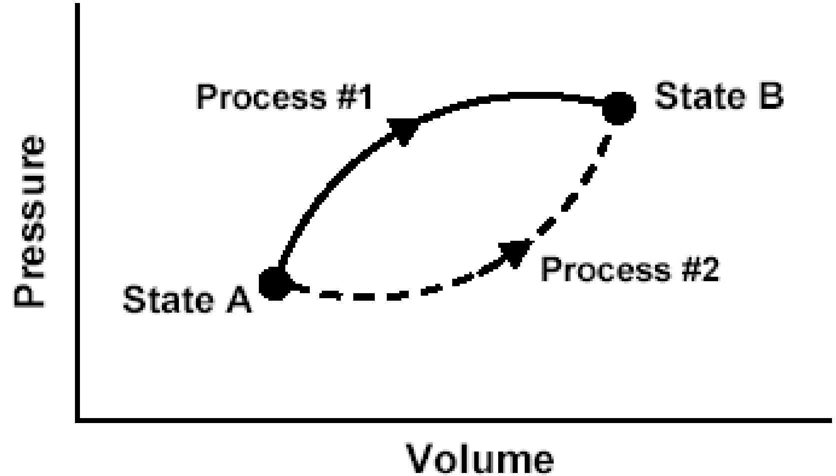
1. Is *W* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2? Explain.

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

3. Which would produce the largest change in the total energy of all the atoms in the system: ***Process #1, Process #2,*** or ***both processes produce the same change?***

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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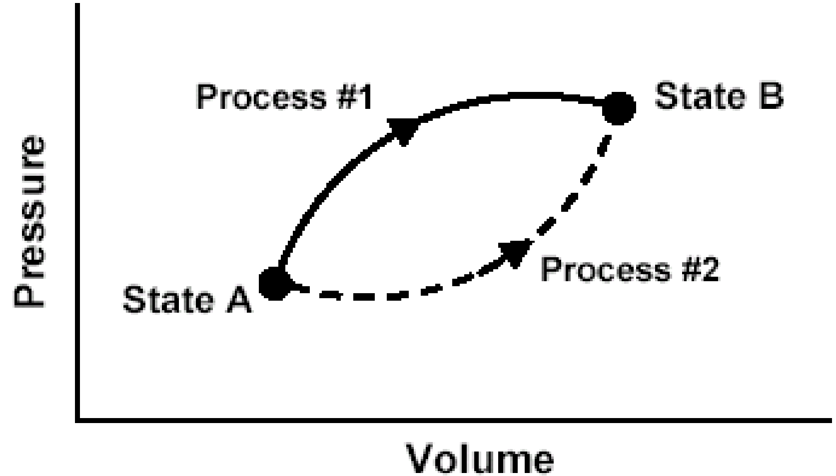

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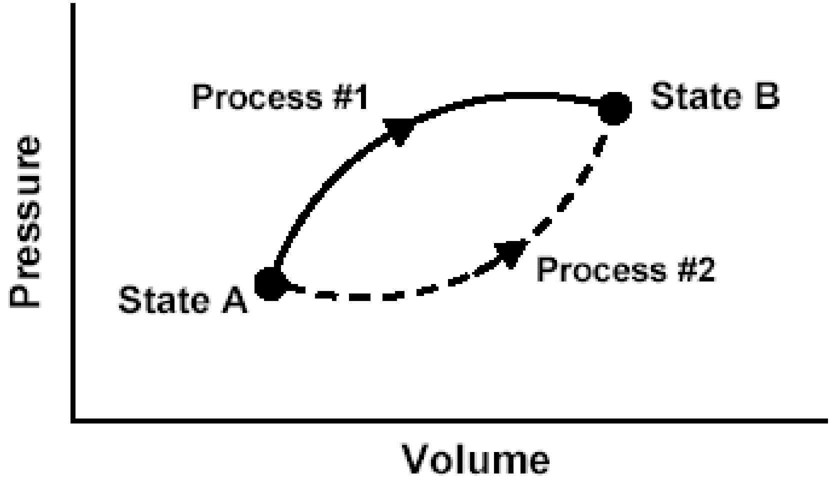

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Responses to Diagnostic Question #2
(Heat question)

	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
$Q_1 > Q_2$ (disregarding explanations)				

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	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
$Q_1 > Q_2$ (disregarding explanations)	**56%**	**40%**	**40%**	**34%**

Examples of "Acceptable" Student Explanations for $Q_1 > Q_2$

"$\Delta U = Q - W$. *For the same* ΔU, *the system with more work done must have more* Q *input so process #1 is greater*."

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"$\Delta U = Q - W$. *For the same* ΔU*, the system with more work done must have more Q input so process #1 is greater.*"

"Q *is greater for process one because it does more work; the energy to do this work comes from the* Q_{in}."

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$Q_1 > Q_2$	**56%**	**40%**	**40%**	**34%**
Correct or partially correct explanation	**14%**	**10%**	**10%**	**19%**
Incorrect, or missing explanation	**42%**	**30%**	**30%**	**15%**

Fewer than 20% of Students are Able to Apply First Law

- Fewer than 20% of students overall could explain why $Q_1 > Q_2$.
- Fewer than 20% of students in interview sample were able to use first law correctly.

→ **Large majority of students finish general physics course unable to apply first law of thermodynamics.**

Consistent with results of Loverude, Kautz, and Heron, Am. J. Phys. (2002), for Univ. Washington, Univ. Maryland, and Univ. Illinois

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- Fewer than 20% of students overall could explain why $Q_1 > Q_2$.
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Students very often attribute state-function properties to process-dependent quantities.

Implementation of Instructional Model

“Elicit, Confront, Resolve”

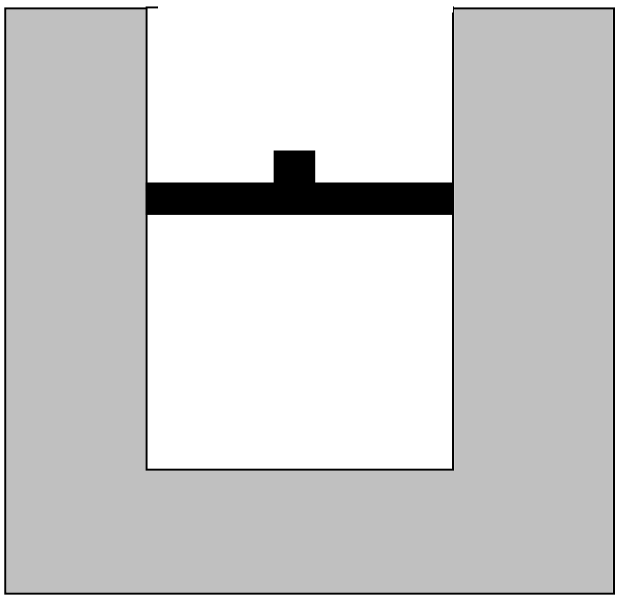
- Allow students to encounter conceptual difficulty
- Students commit themselves to a response

Implementation of Instructional Model

"Elicit, Confront, Resolve"

- Allow students to encounter conceptual difficulty
- Students commit themselves to a response
- Guide students along alternative reasoning track
- Students compare responses and resolve discrepancies

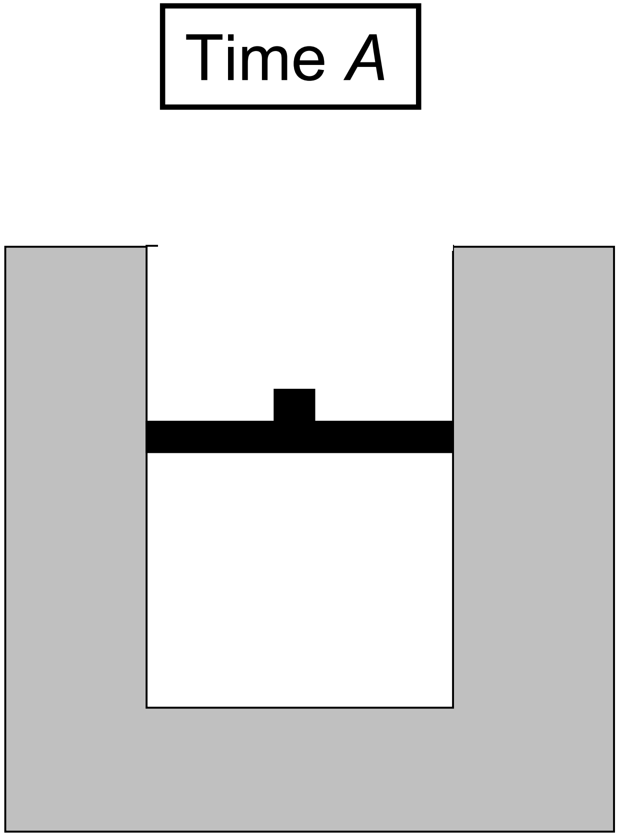
Cyclic Process Worksheet
(adapted from interview questions)



Worksheet Strategy

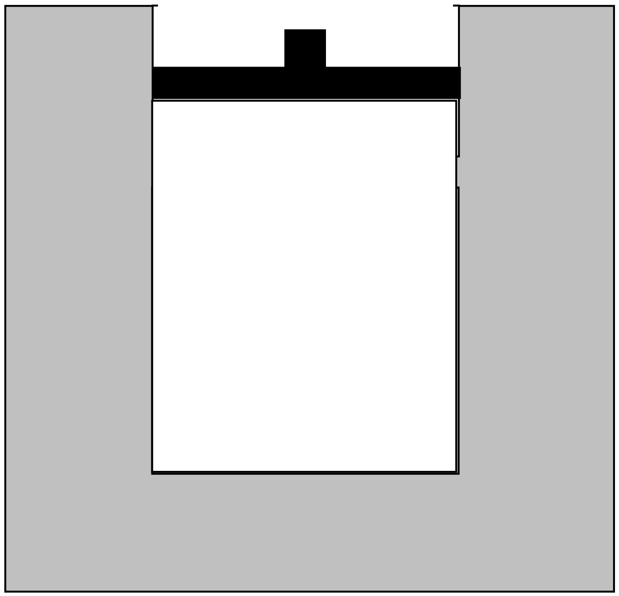
- First, allow students to read description of entire process and answer questions regarding work and heat.

System heated



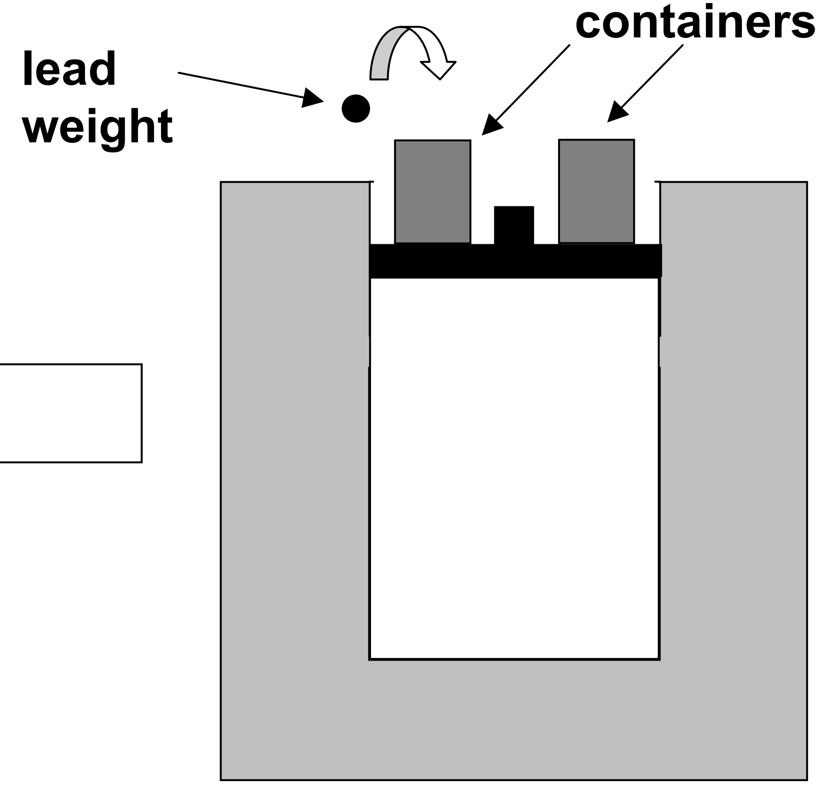
Time *B*

System heated, piston goes up.



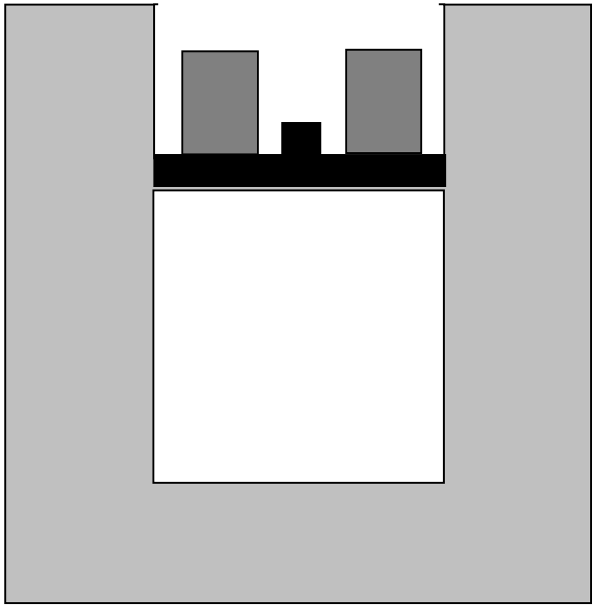
Time *B*

Weights added

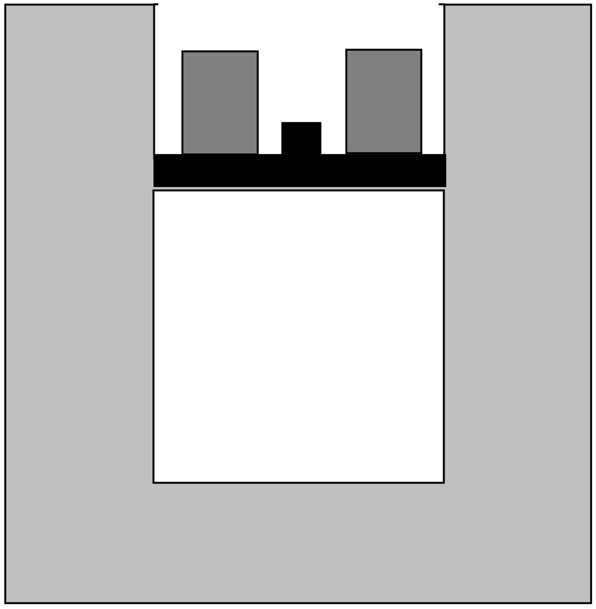


Time *C*

Weights added, piston goes down.



Time *C*



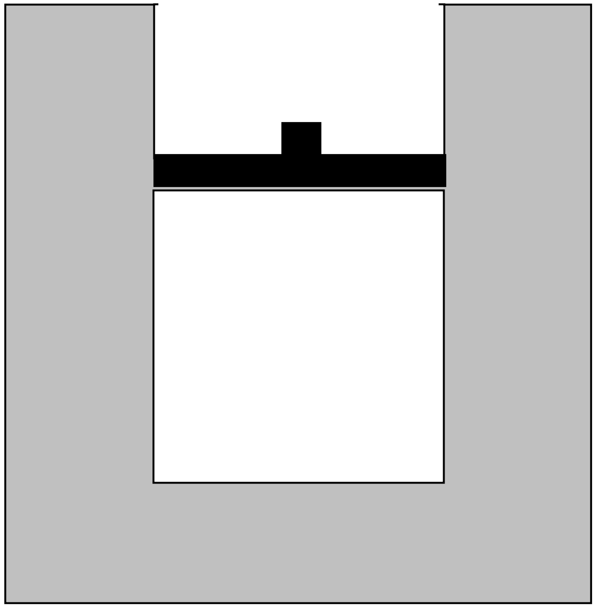
Weights added, piston goes down.

[Temperature remains constant]

Time *C*

Temperature *C*

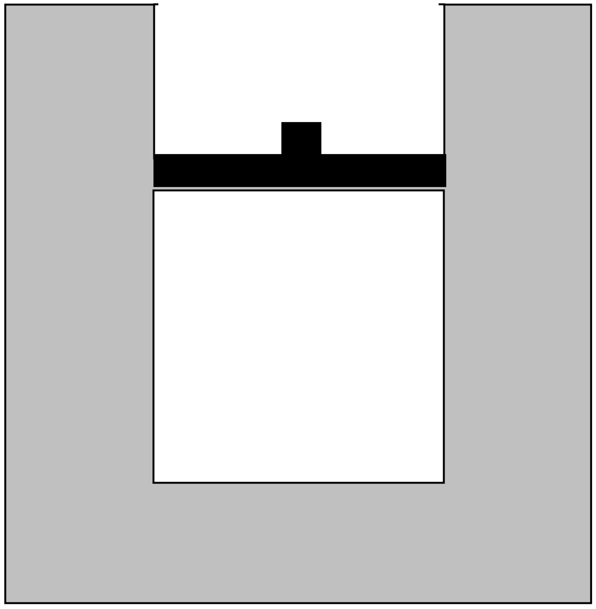
Piston locked

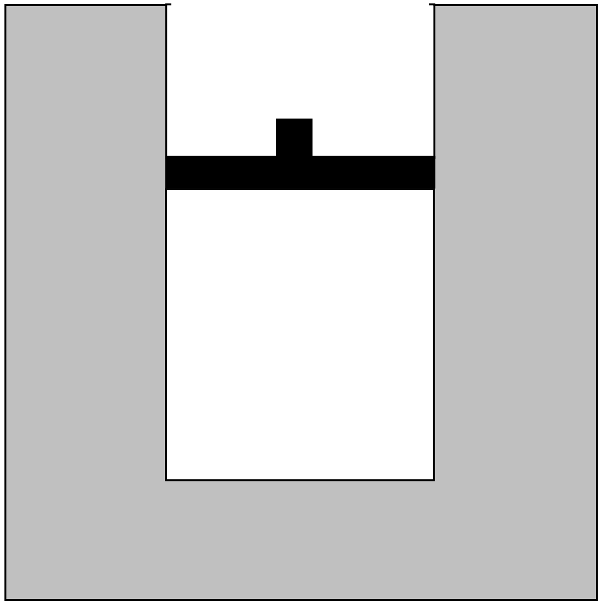


Time *D*

Temperature *D*

Piston locked, temperature goes down.





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

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

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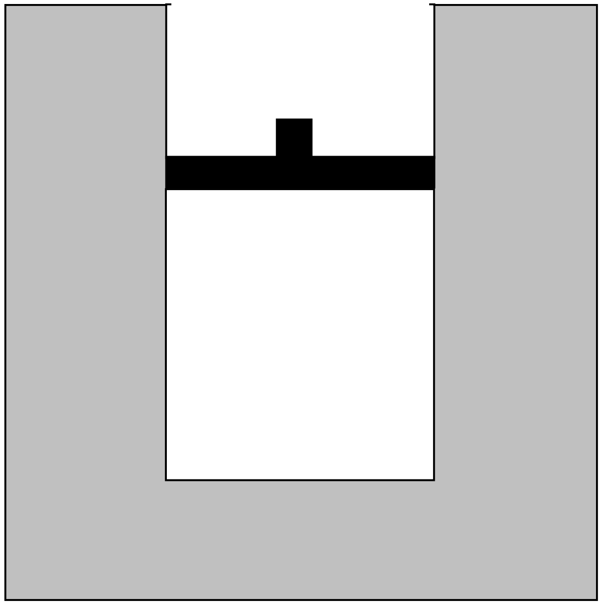

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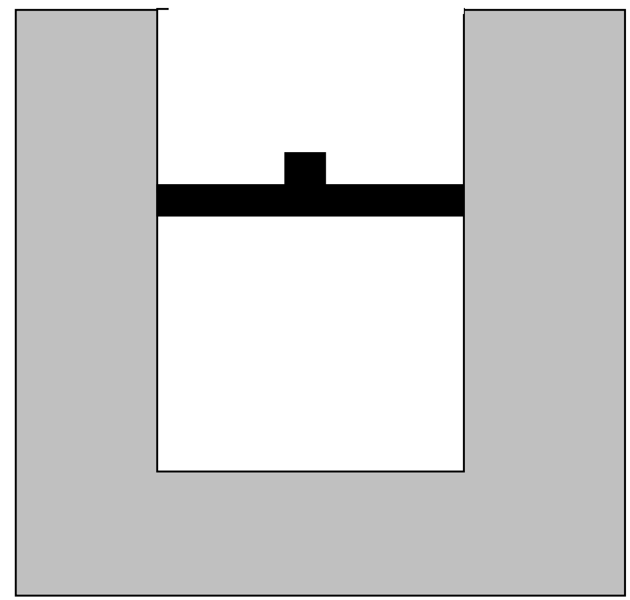
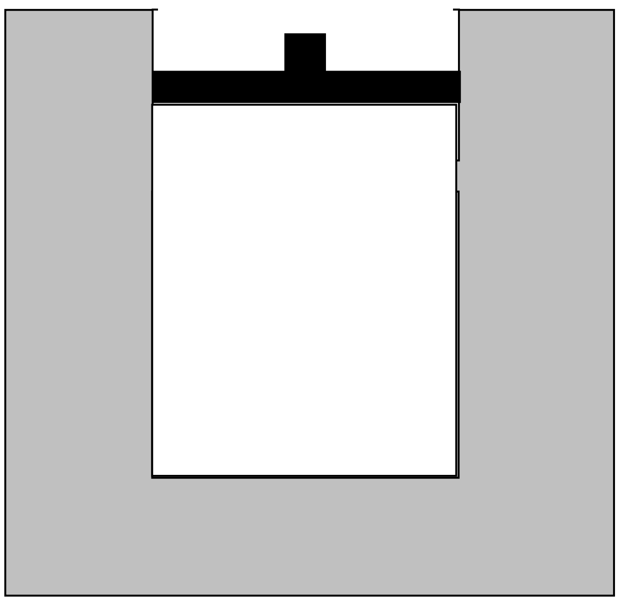
Worksheet Strategy

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

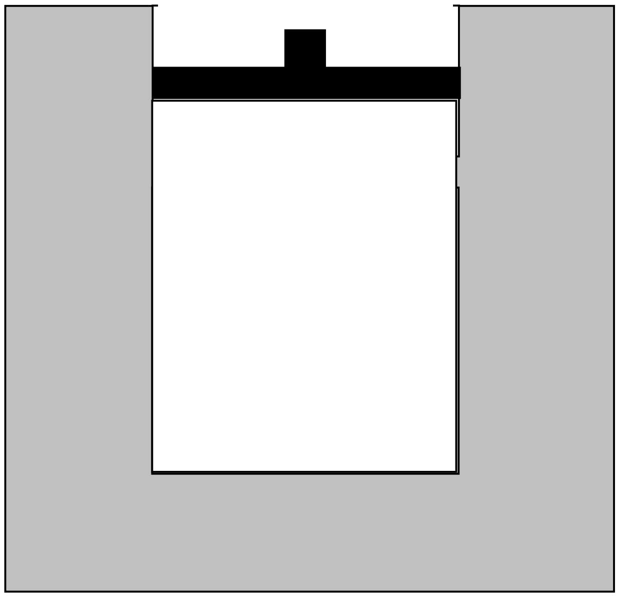
Time *A*



Time *B*



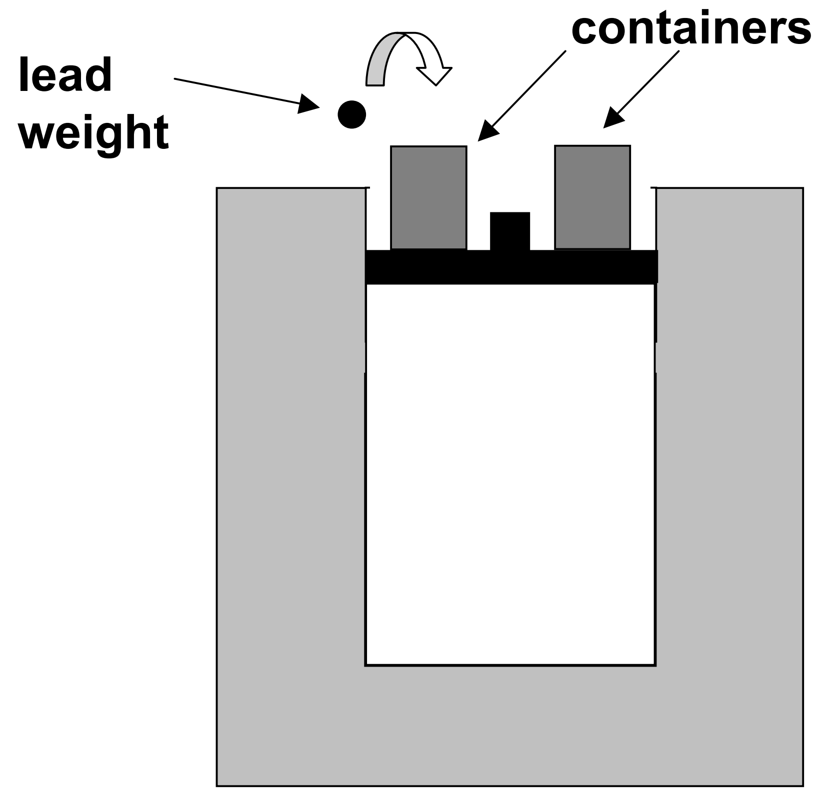
Time *B*



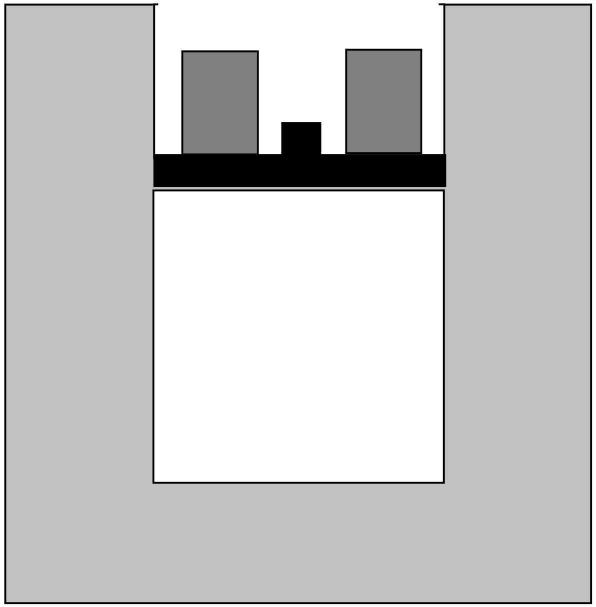
1) For the process A → B, is the work done by the system (W_{AB}) *positive*, *negative*, or *zero*?

Explain your answer.

Time *B*

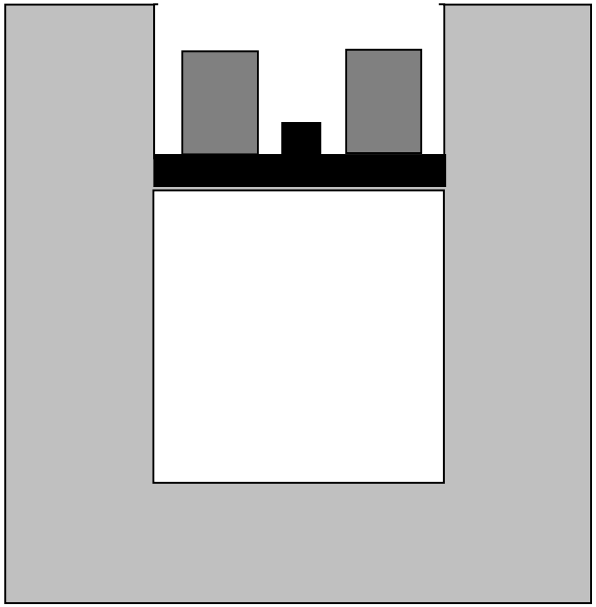


Time *C*



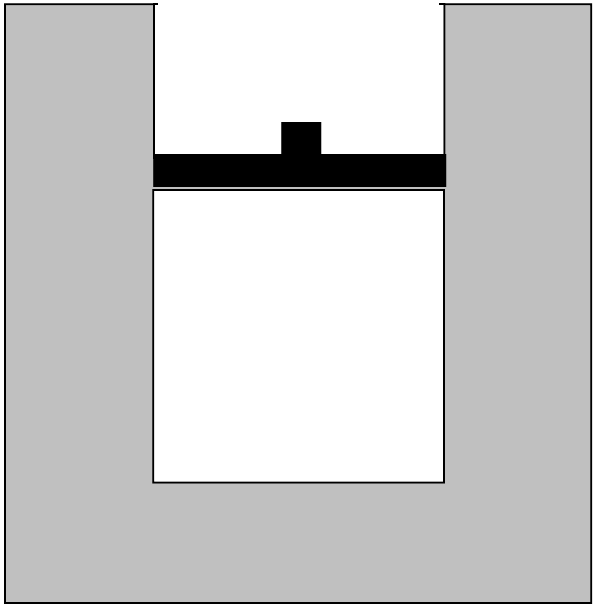
Time *C*

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



Time *C*

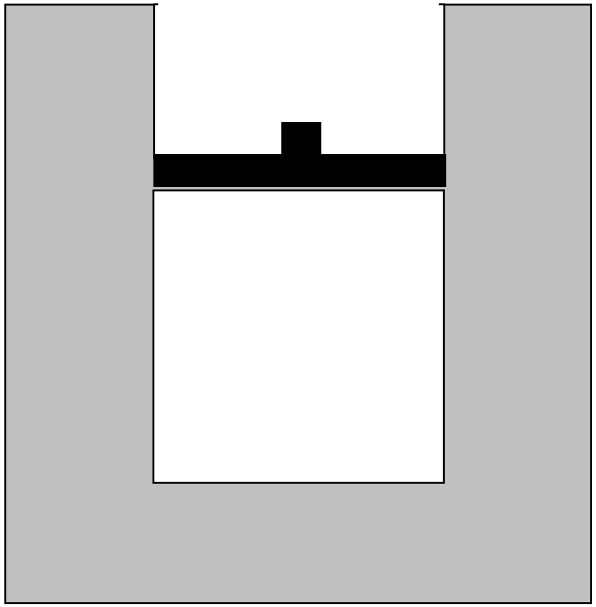
Temperature *C*



Time *D*

Temperature *D*

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



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

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

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

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

largest ______________________________ *smallest*

Explain your reasoning.

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

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

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

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

Explain your reasoning.

Worksheet Strategy

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

Worksheet Strategy

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

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

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

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

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

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

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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

Current Work: Advanced-Level Thermal Physics Course

Funded by Physics Division of NSF

- 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

Course and Students

- **Topics:** Approximately equal balance between classical macroscopic thermodynamics, and statistical thermodynamics (Texts: Sears and Salinger; Schroeder)

- **Students enrolled, 2004** ($N_{initial}$ = 20):
  - all but three were physics majors or physics/engineering double majors
  - all but one were juniors or above
  - all had studied thermodynamics

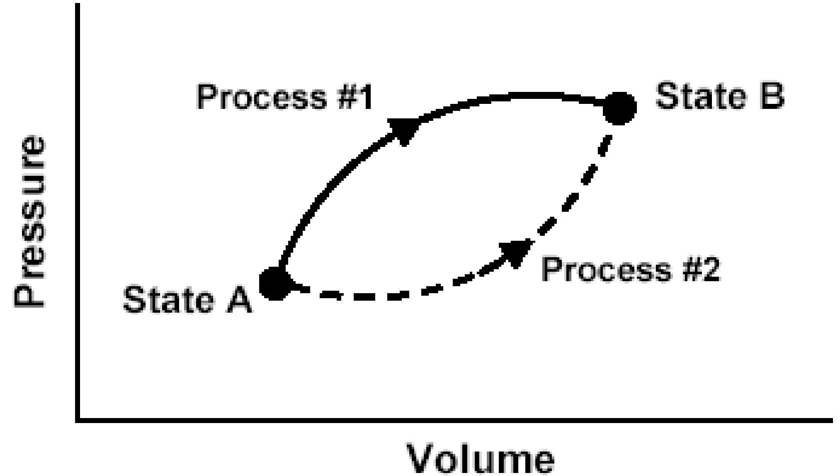
Performance Comparison:
Upper-level vs. Introductory Students

- Diagnostic questions given to students in introductory calculus-based course *after* instruction was complete

- Written pre-test questions given to Thermal Physics students on *first day* of class

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

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



$$W_1 > W_2$$

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

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

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

Responses to Diagnostic Question #1

(Work question)

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	**2002** Introductory Physics (Post-test) Interview Sample (*N*=32)	**2004** Thermal Physics (Pretest) (*N*=21)
$W_1 > W_2$			
$W_1 = W_2$			
$W_1 < W_2$			

Responses to Diagnostic Question #1
(Work question)

$W_1 = W_2$			

Responses to Diagnostic Question #1
(Work question)

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**		
$W_1 = W_2$	**30%**		

Responses to Diagnostic Question #1
(Work question)

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

Responses to Diagnostic Question #1
(Work question)

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	**2002** Introductory Physics (Post-test) Interview Sample (*N*=32)	**2004** Thermal Physics (Pretest) (*N*=20)
$W_1 = W_2$	**30%**	**22%**	**25%**

Responses to Diagnostic Question #1
(Work question)

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$W_1 = W_2$	30%	22%	25%

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

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:
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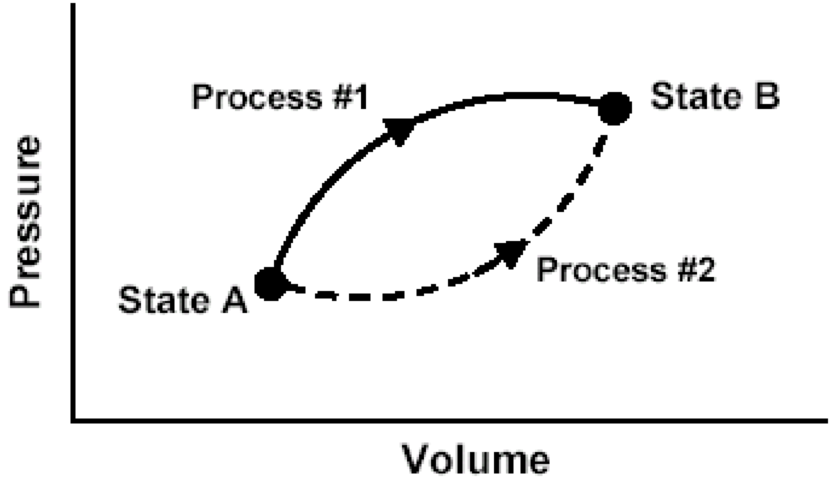

[In these questions, ***W*** represents the work done ***by*** the system during a process; ***Q*** represents the heat ***absorbed*** by the system during a process.]

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

2. Is Q for Process #1 ***greater than, less than***, or ***equal to*** that for Process #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)**		
$Q_1 > Q_2$	**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)	2004 Thermal Physics (Pretest) (*N*=20)
$Q_1 > Q_2$	**45%**	**34%**	**30%**

Responses to Diagnostic Question #2
(Heat question)

	1999-2001 Introductory Physics (Post-test) Written Sample (N=653)	**2002** Introductory Physics (Post-test) Interview Sample (N=32)	**2004** Thermal Physics (Pretest) (N=20)
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Correct or partially correct explanation			

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Correct or partially correct explanation	11%	19%	30%

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

Performance of upper-level students significantly better ($p < 0.01$) than introductory students in *written* sample

Other Comparisons

- Performance of upper-level students on written pretest was not significantly different from interview sample (high-performing introductory students) on post-instruction questions related to:
  - Cyclic processes
  - Isothermal processes
  - Thermal reservoirs

Outline

Physics Education as a Research Problem

- Goals and Methods of Physics Education Research
- Some Specific Issues

Research-Based Instructional Methods

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

Research-Based Curriculum Development

- A “model” problem: student understanding of gravitation
- Investigation of student reasoning in thermodynamics

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- 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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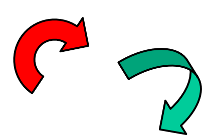

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