A Research-Based Approach to the Learning and Teaching of Physics

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Collaborators

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– Jack Dostal (ISU, M.S. 2005)
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Funding

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

Outline

1. Physics Education as a Research Problem

    Methods of physics education research

2. Research-Based Instructional Methods

    Principles and practices

3. Research-Based Curriculum Development

    A "model" problem: law of gravitation

4. Recent Work: Student Learning of Thermal Physics

    Research and curriculum development

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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.

Role of Researchers in Physics Education

- Carry out in-depth investigations of student thinking in physics
  - provide basis for “pedagogical content knowledge”
- Develop and assess courses and curricula:
  - for introductory and advanced undergraduate courses
  - for physics teacher preparation

Progress in Teacher Preparation

- Advances in research-based physics education have motivated changes in physics teacher preparation programs.
- There is an increasing focus on research-based “active-engagement” instructional methods and curricula.
- **Examples:** *Physics by Inquiry* curriculum (Univ. Washington); Modeling Workshops (Arizona State U.)

Example: Course for Physics-Teacher Preparation

- Course taught by D.E.M., for students planning to teach high-school physics (at Iowa State U.)
  - includes pre-service and in-service teachers, students with and without B.A., diverse majors
- Reading and discussion of physics education research literature
- In-class instruction using research-based curricular materials (guided by course instructor)
- Students prepare and deliver own lesson
  - modeled on research-based instructional materials

Example: Inquiry-Based Physics Course for Non-technical Students

- Developed and taught by D.E.M., targeted especially at education majors (i.e., “teachers in training”).
- Taught at Southeastern Louisiana University for 8 consecutive semesters; average enrollment: 14
- One-semester course, met 5 hours per week in lab
  - focused on hands-on activities; no formal lecture.
- Inquiry-based learning: targeted concepts not told to students before they work to “discover” them through group activities.

Research and Scholarship in Physics-Teacher Preparation

- Forthcoming book of collected papers
- Jointly published by American Physical Society and American Association of Physics Teachers
- *Editor:* D.E.M.
- *Associate Editor:* Peter Shaffer (U. Washington)

Research Basis for Improved Learning

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  "…the ways of representing and formulating a subject that make it comprehensible to others….an understanding of what makes the learning of specific topics easy or difficult…knowledge of the [teaching] strategies most likely to be fruitful…"

Research on Student Learning: Some Key Results

- Students' *subject-specific* conceptual difficulties play a significant role in impeding learning;

- Inadequate *organization* of students' knowledge is a key obstacle.
  - need to improve linking and accessibility of ideas

- Students' *beliefs and practices* regarding learning of science should be addressed.
  - need to stress reasoning instead of memorization

A Model
for Students' Knowledge Structure

[E. F. Redish, *AJP* (1994), *Teaching Physics* (2003)]

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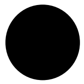

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  - *tightly linked network of well-understood concepts*

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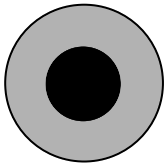

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- Middle "gray" ring: students' partial and imperfect knowledge [Vygotsky: "Zone of Proximal Development"]
  - *knowledge in development: some concepts and links strong, others weak*

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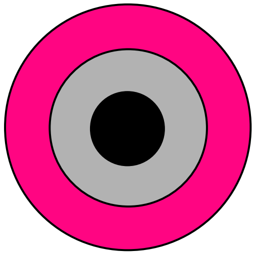

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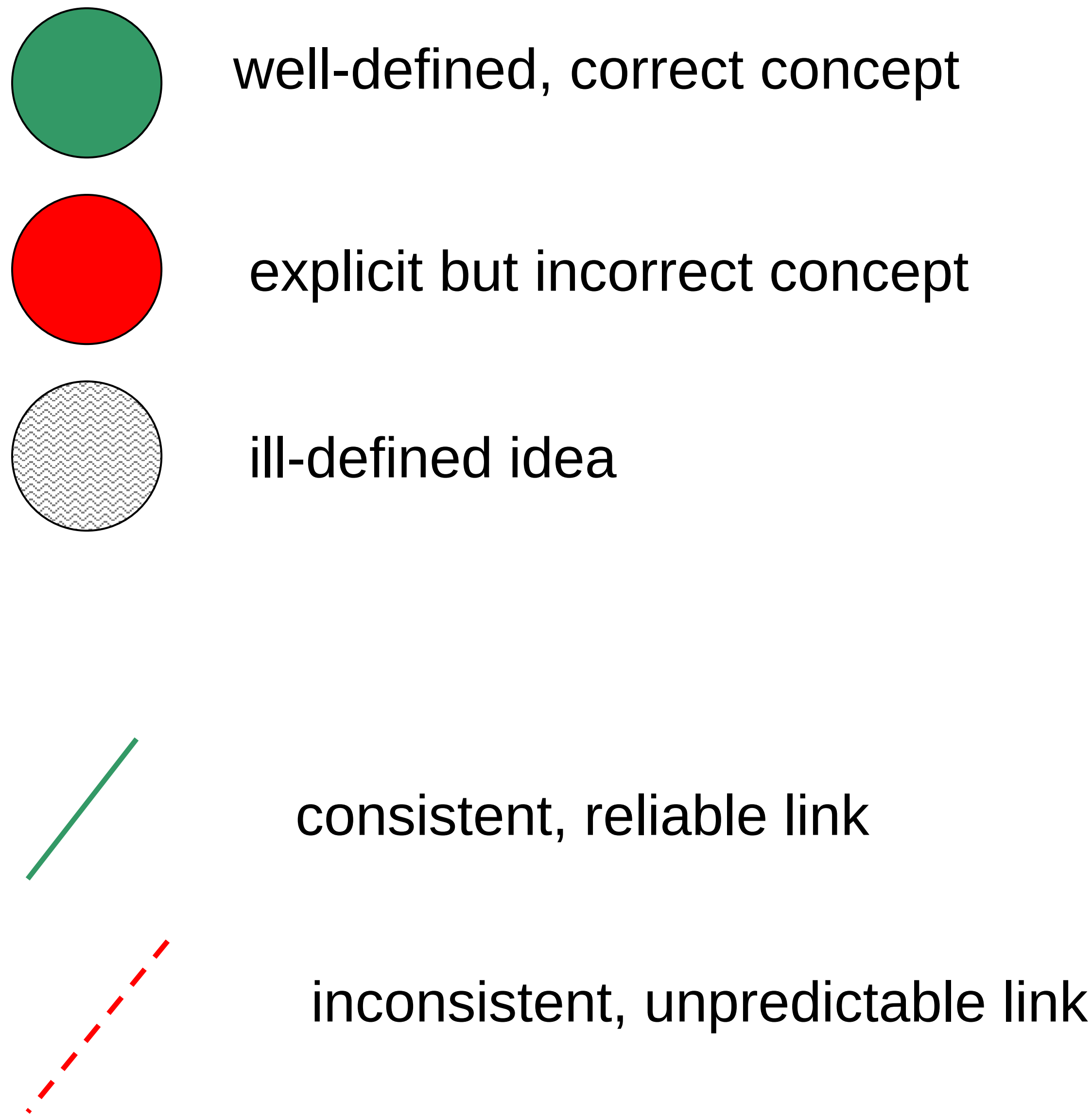
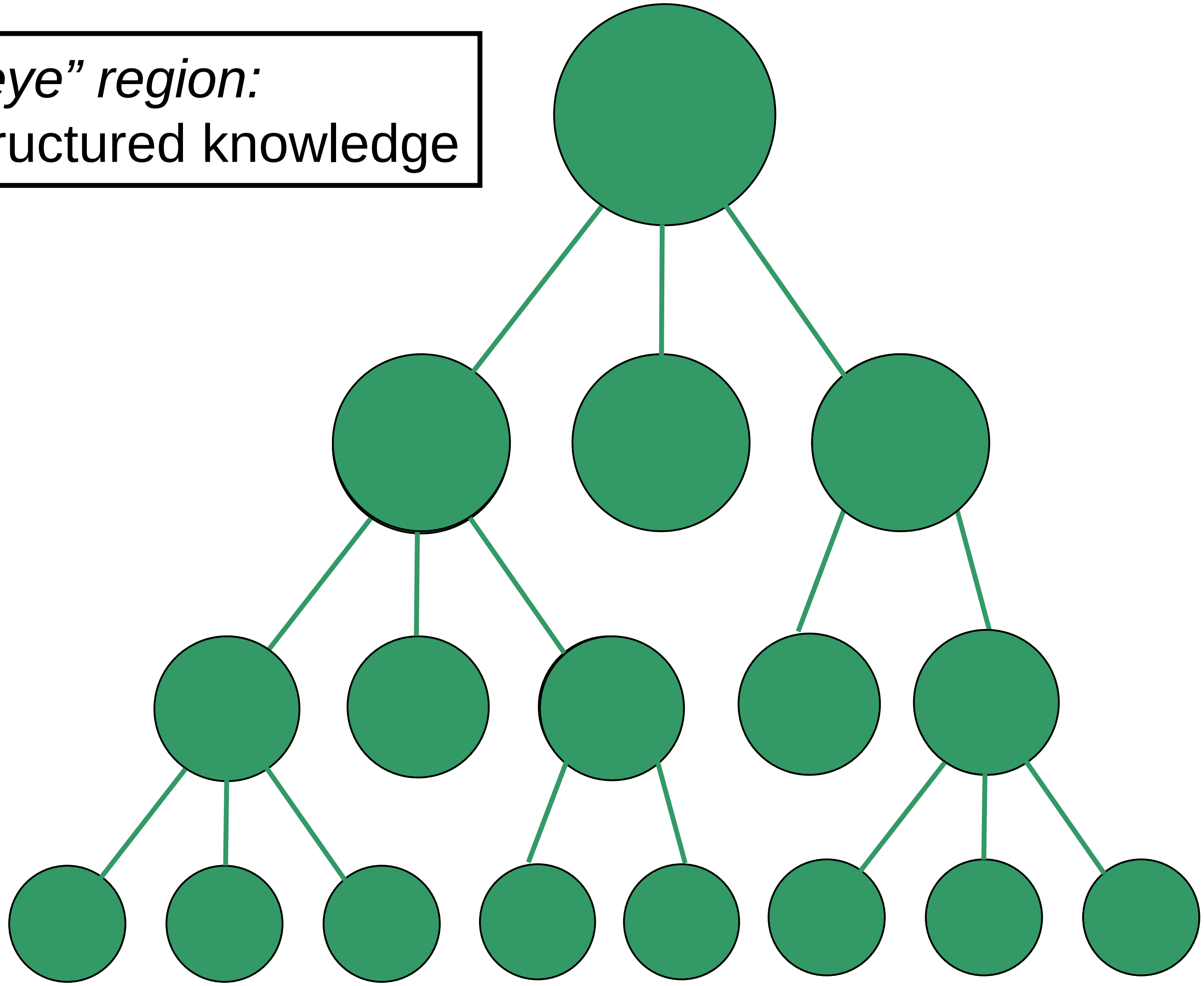
- Outer "white" region: what students don't know at all
  - *disconnected fragments of poorly understood ideas*

Schematic Representation of Knowledge Structure…

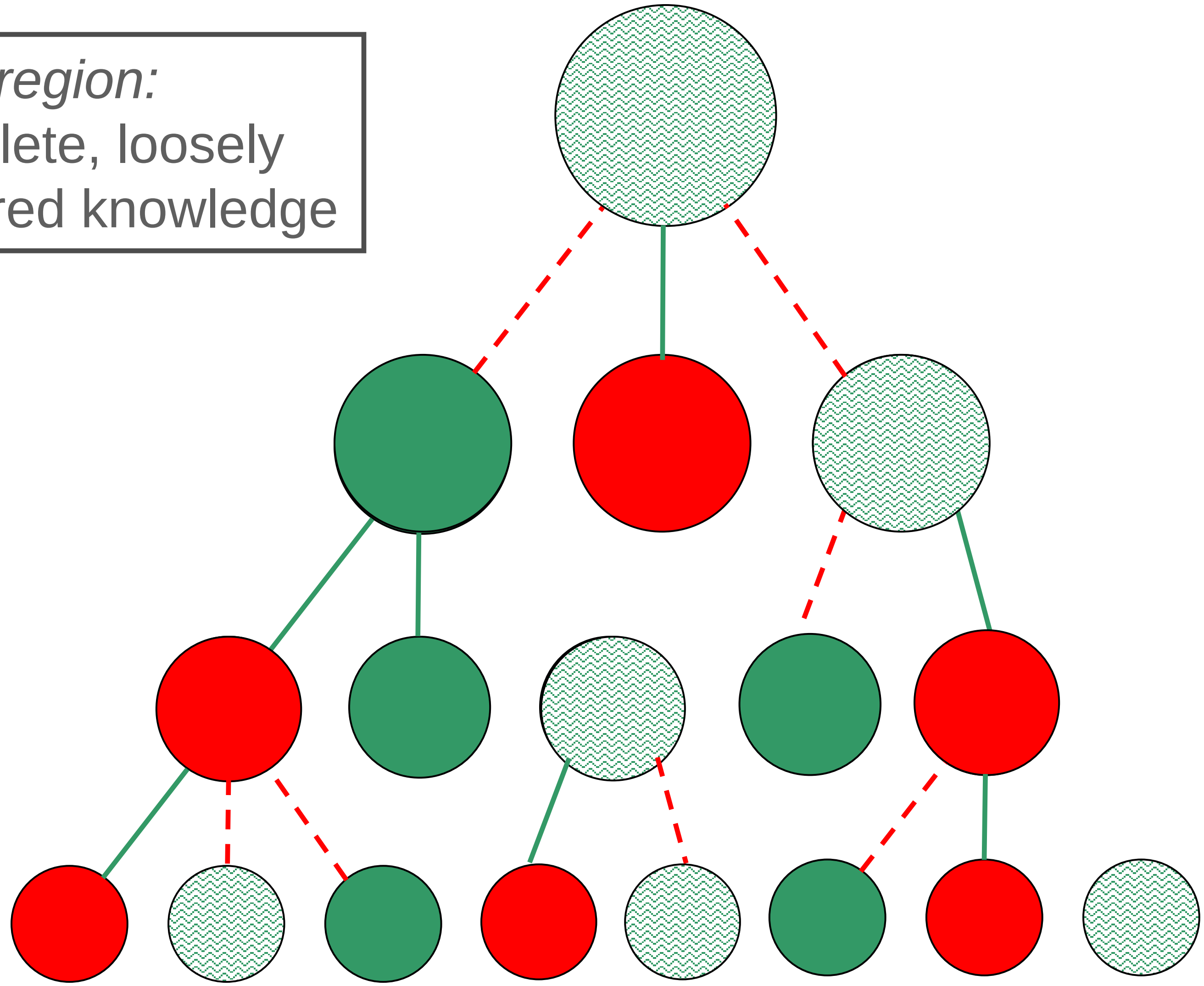

well-defined, correct concept
explicit but incorrect concept
ill-defined idea
consistent, reliable link
inconsistent, unpredictable link

“Bulls-eye” region:
Well-structured knowledge



[F. Reif, Am. J. Phys. (1995)]

“Gray” region:
incomplete, loosely structured knowledge



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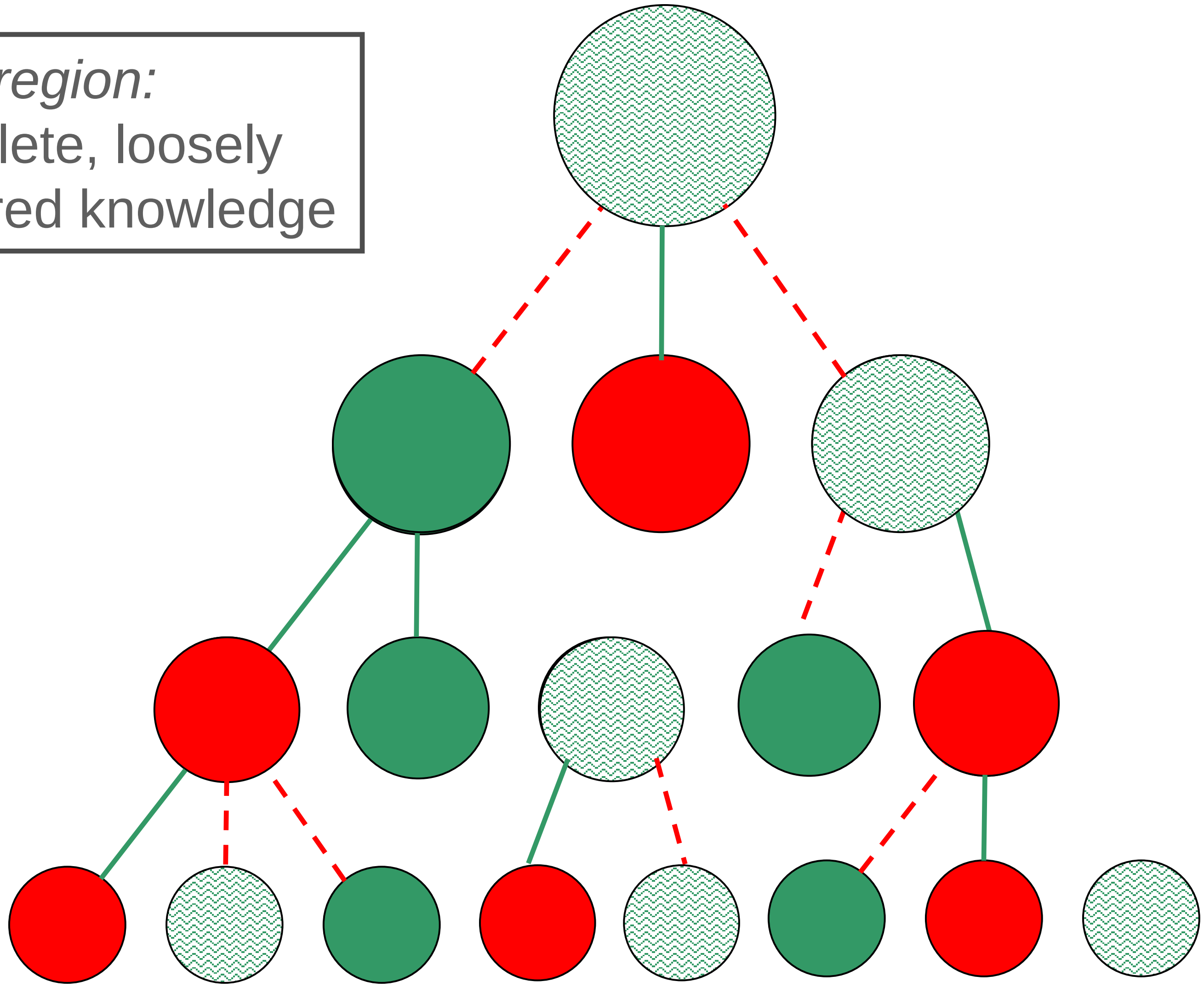

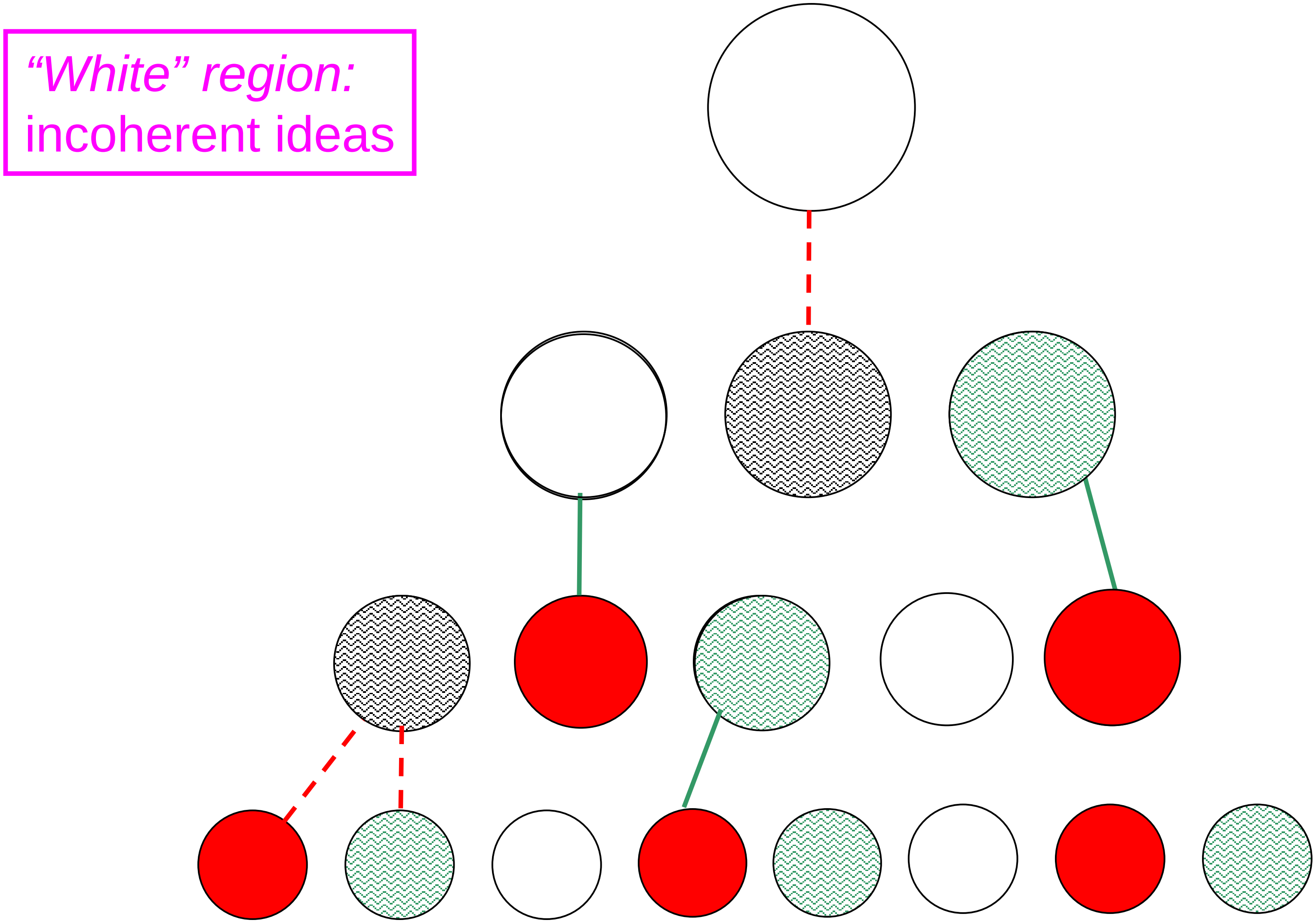
“White” region:
incoherent ideas

Teaching Effectiveness, Region by Region

- *In central black region:* difficult to make significant relative gains
- *In white region:* learning gains minor, infrequent, and poorly retained.
- *Teaching most effective when targeted at gray:* Analogous to substance near phase transition; a few key concepts and links can catalyze substantial leaps in student understanding.

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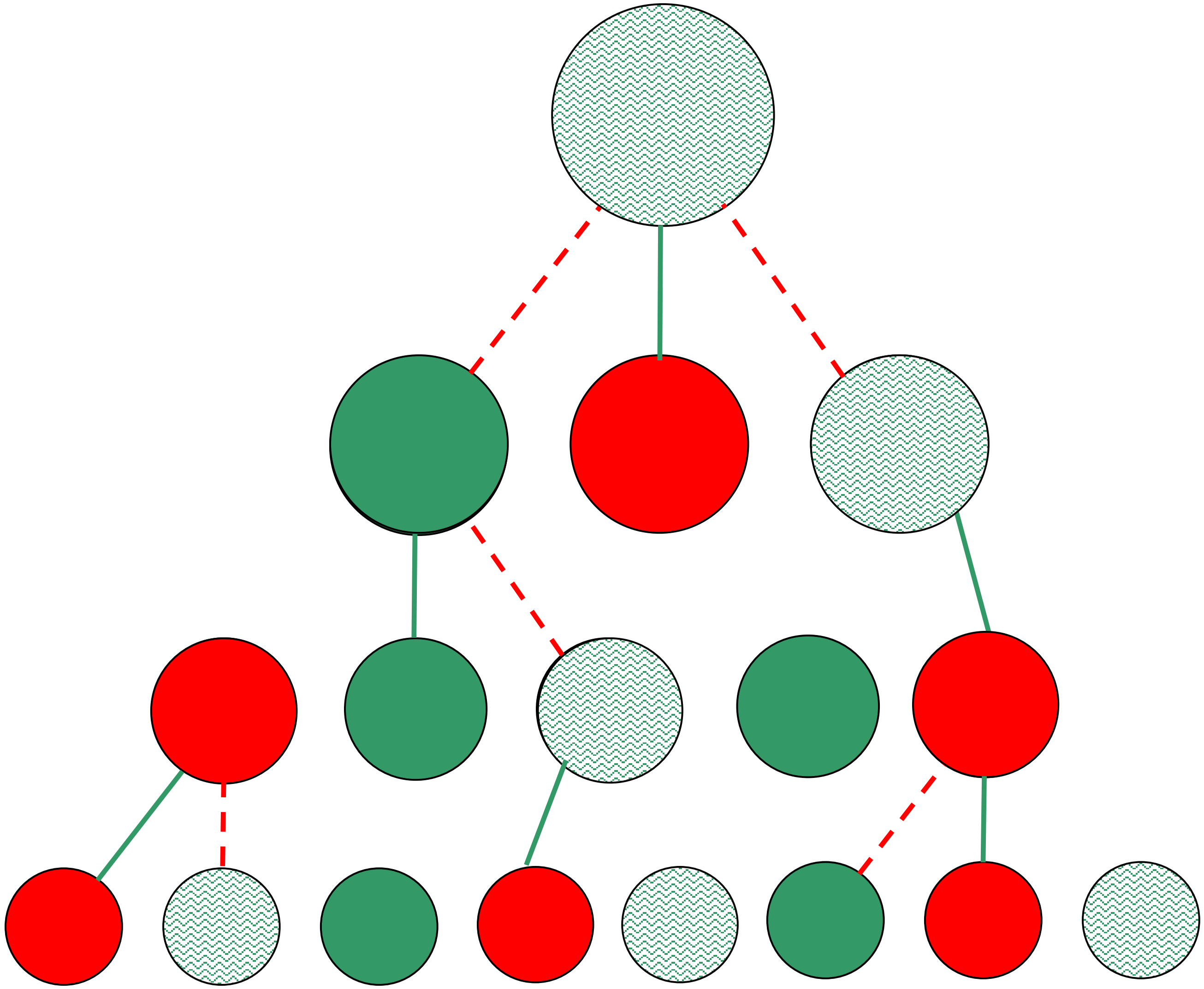
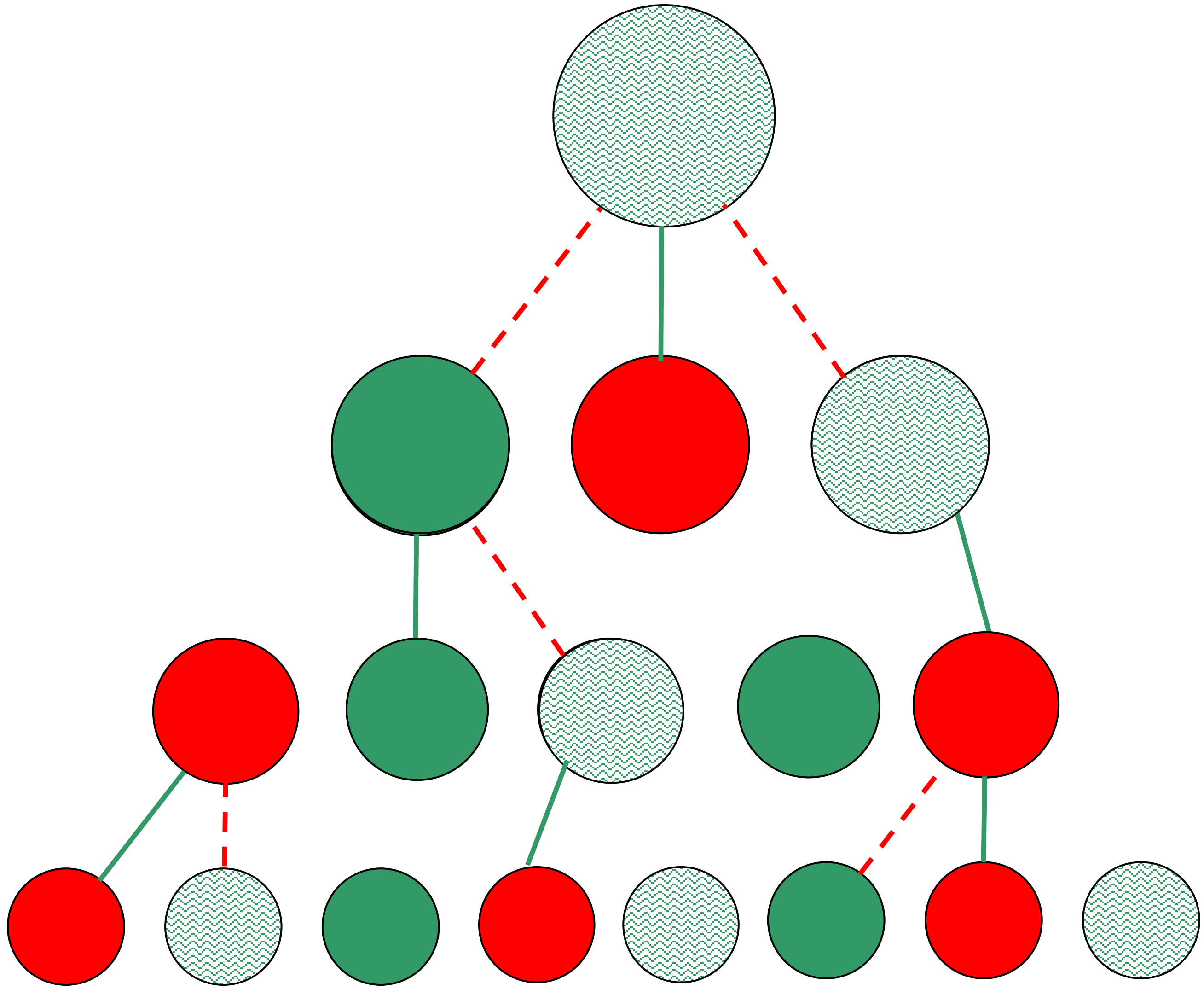
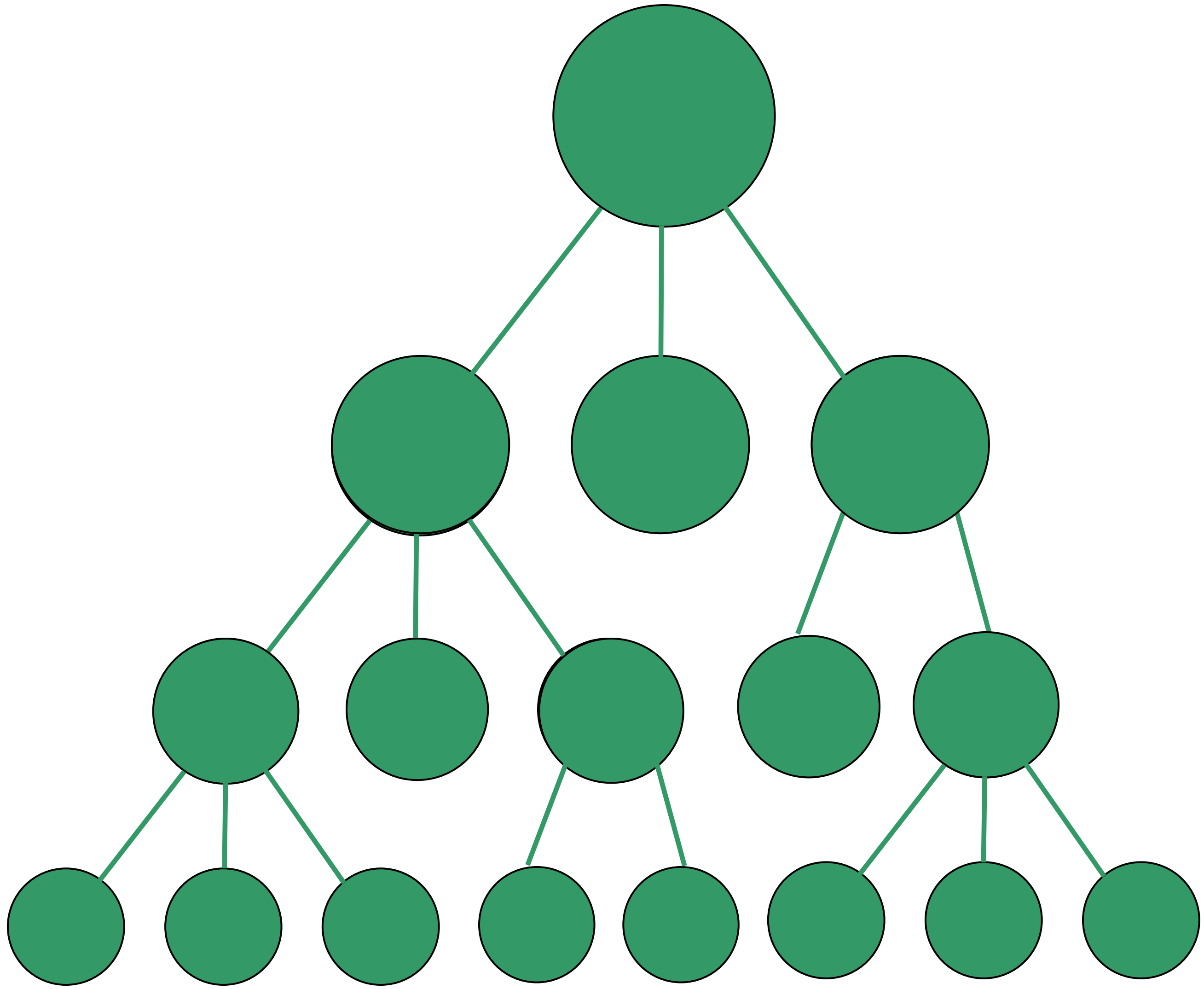


Research Task: map out gray region



Instructional Task: address difficulties in gray region



Instructional Goal: well-organized set of coherent concepts

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Research and curriculum development

Research-Based Instruction

- Recognize and address students' pre-instruction "knowledge state" and learning tendencies, including:
  - subject-specific learning difficulties
  - potentially productive ideas and intuitions
  - student learning behaviors

- Guide students to address learning difficulties through structured and targeted problem-solving activities.

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

Research in physics education suggests that:

- 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

- "*guided-inquiry*" methodology: guide students with leading questions, through structured series of research-based problems

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.

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.
- Incorporate cooperative **group work** using both multiple-choice and free-response items

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

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➢ *Analogous to in-class strategies used with* Just-In-Time Teaching *(Novak, Gavrin, Christian, and Patterson, 1999)*

"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")

[a variant of Mazur's "Peer Instruction"]

Interactive Question Sequence

- Set of closely related questions addressing diverse aspects of single concept
- Progression from easy to hard questions
- Use multiple representations (diagrams, words, equations, graphs, etc.)
- Emphasis on qualitative, not quantitative questions, to reduce "equation-matching" behavior and promote deeper thinking

Results of Assessment

- Learning gains on qualitative problems are well above national norms for students in traditional courses.

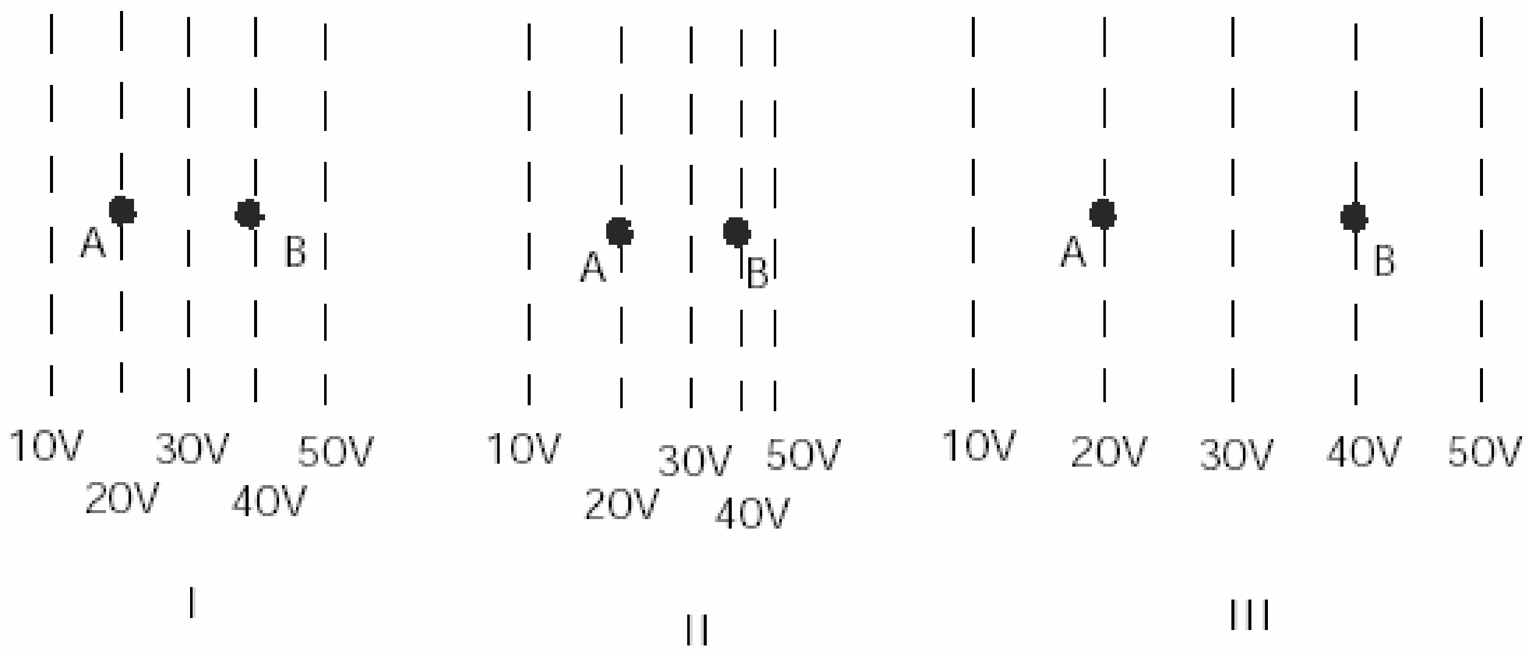
- Performance on quantitative problems is comparable to (or slightly better than) that of students in traditional courses.

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).*

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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%**

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ISU 1998	70	**30%**	
ISU 1999	87	**26%**	
ISU 2000	66	**29%**	

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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%

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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%

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Research-Based Curriculum Development

- Investigate student learning in actual classes; 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]

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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.*

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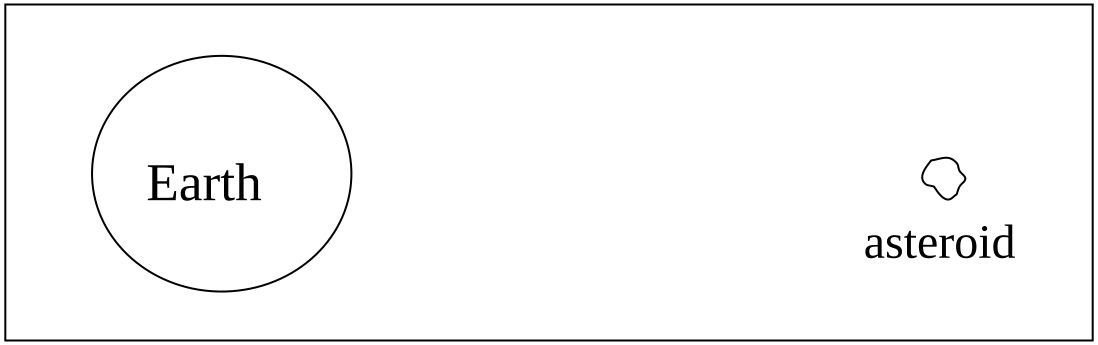
- Worksheets developed to address learning difficulties; tested in calculus-based physics course Fall 1999

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.*

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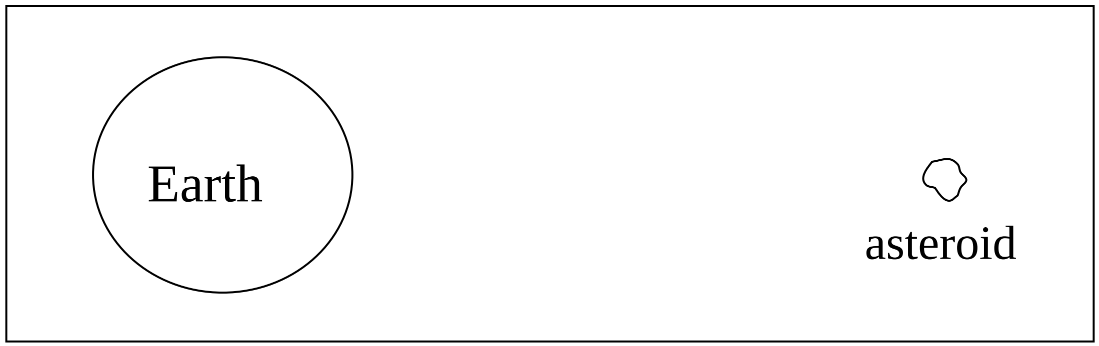

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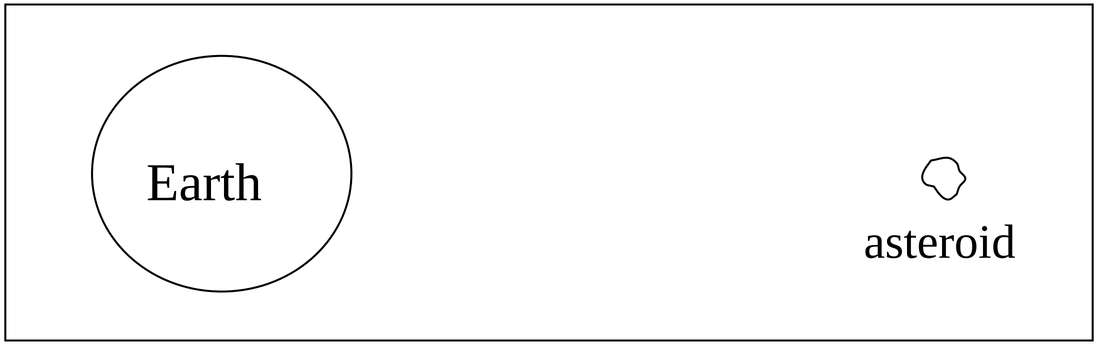

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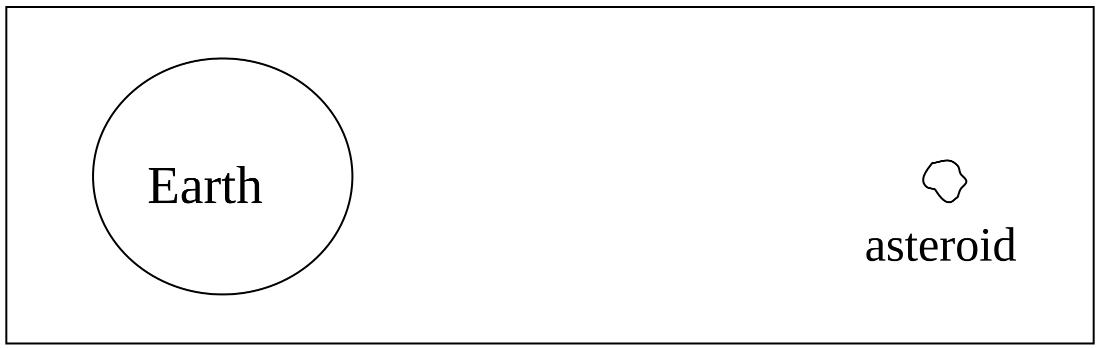

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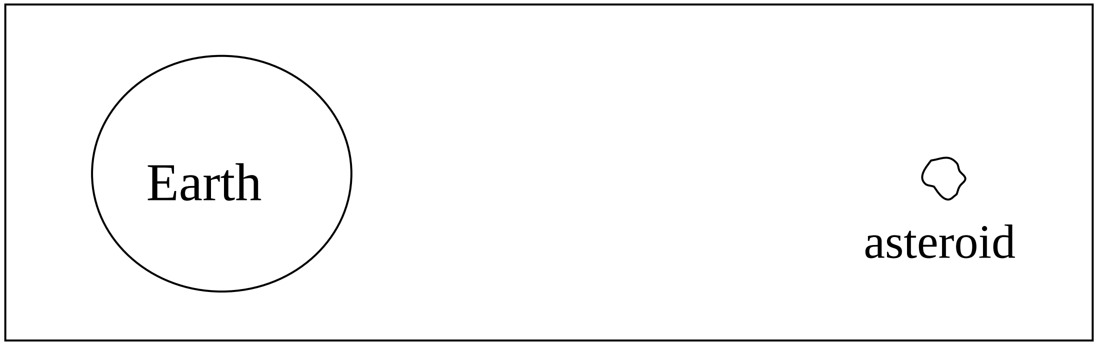

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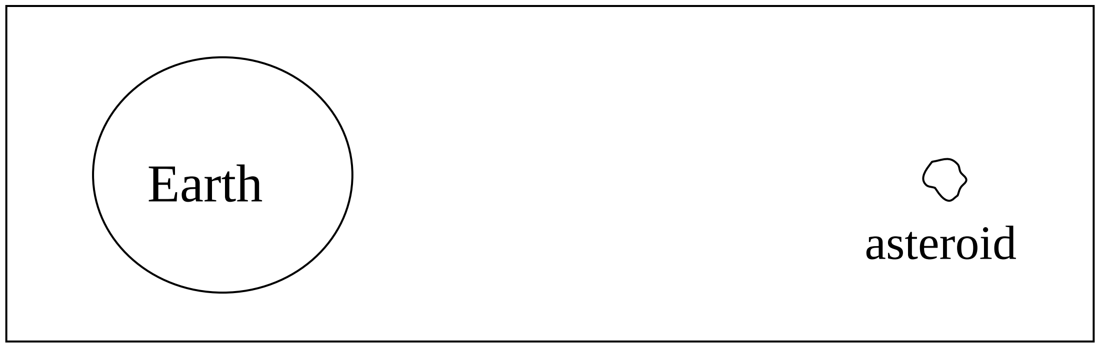

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Most students claim that Earth exerts greater force because it is larger

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*

- 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)

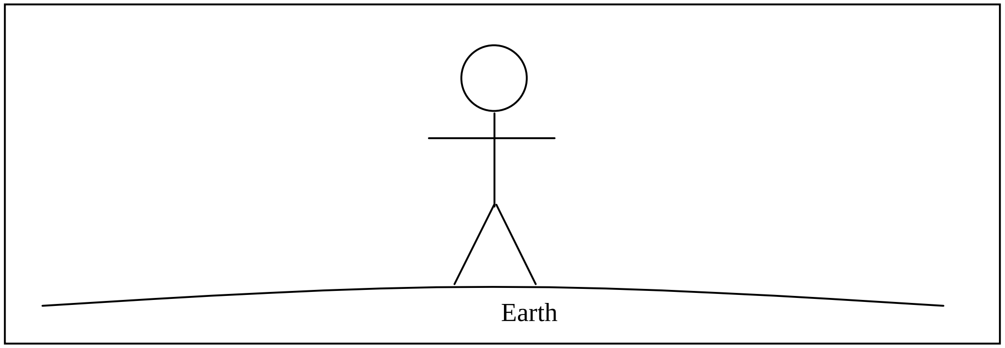
- Design based on research, as well as instructional experience

- Targeted at difficulties with Newton’s third law, and with use of proportional reasoning in inverse-square force law

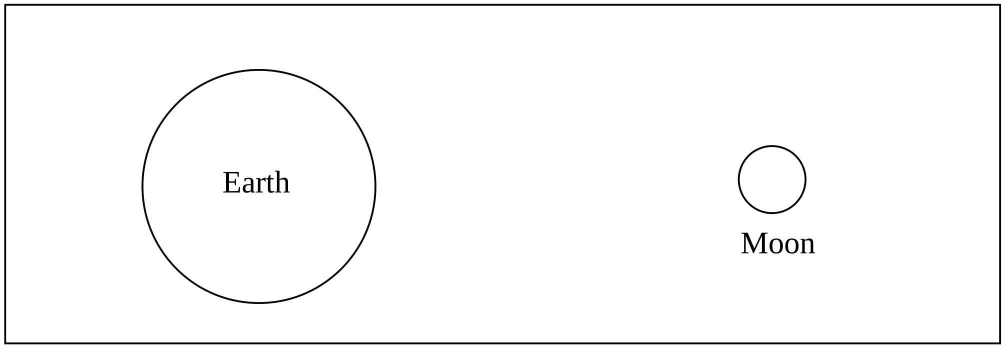
Name______________________

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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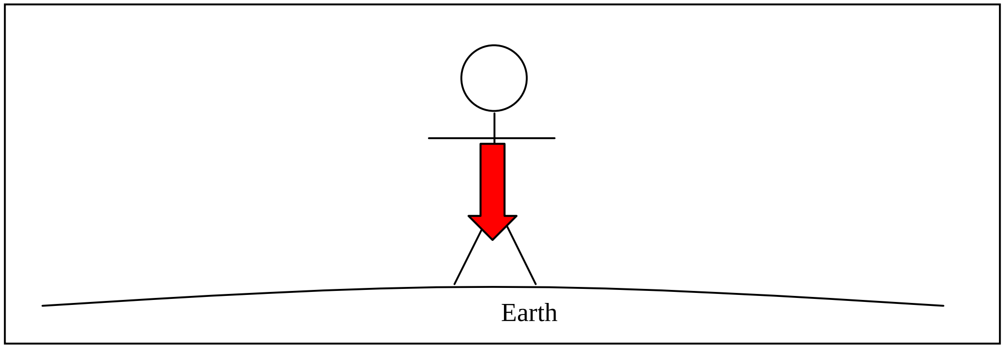

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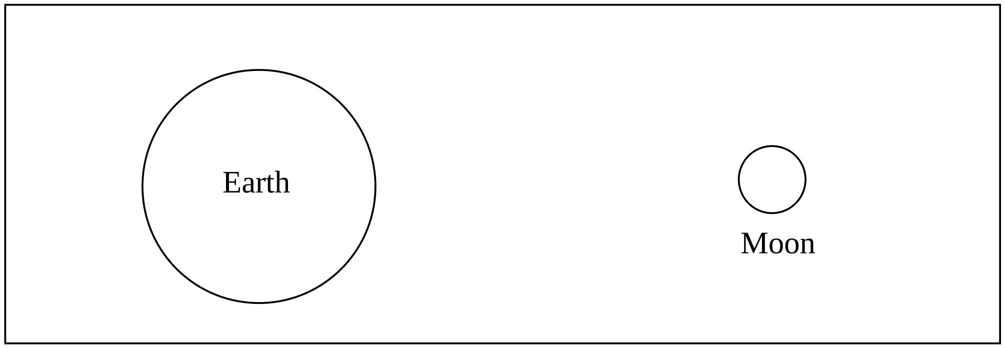

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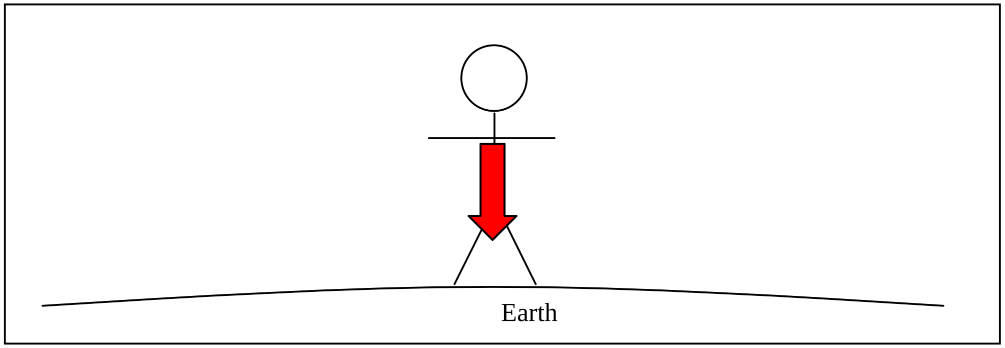

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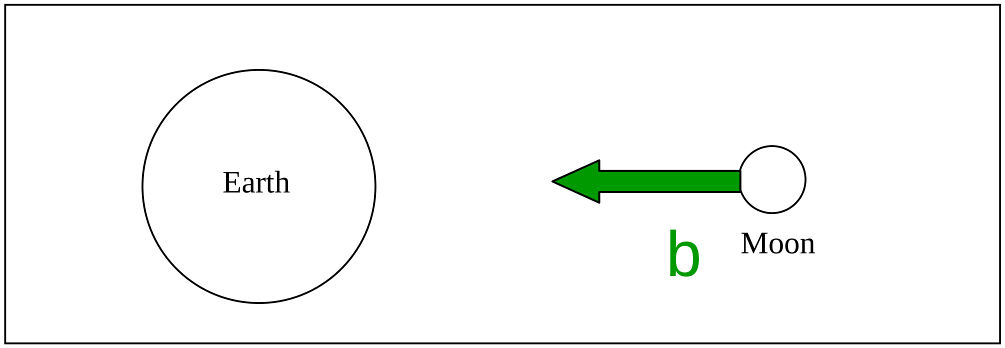

c) Now, in the same picture (above), draw an arrow which represents the force exerted ***by*** the Moon ***on*** the Earth. Label this arrow **(c)**. Remember to draw the arrow with the correct length and direction as compared to the arrow you drew in **(b)**.

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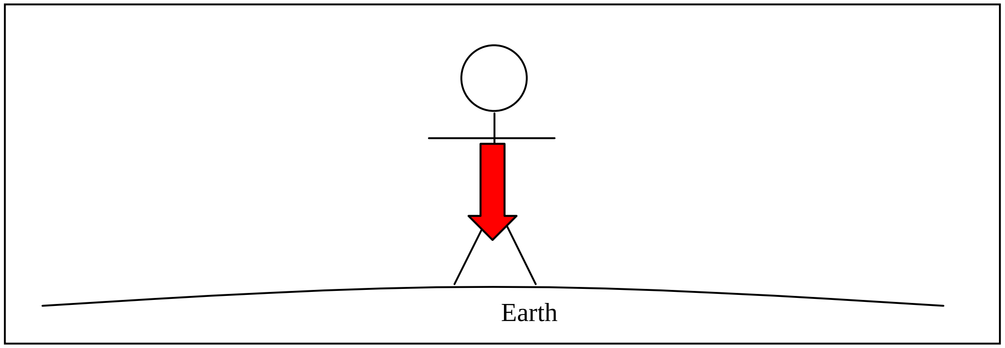

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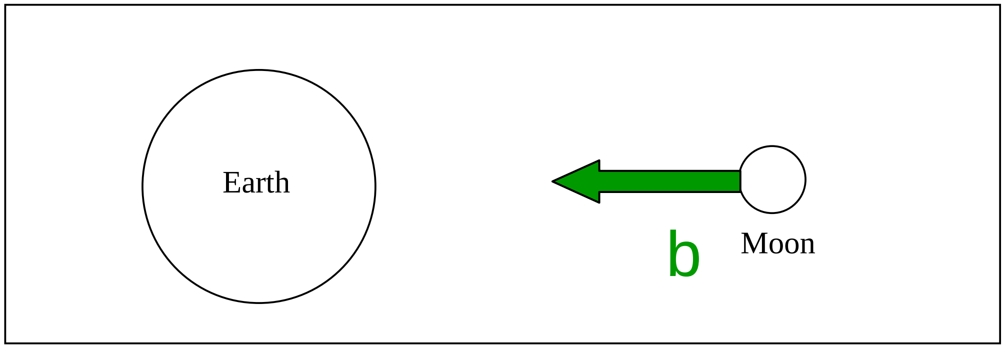

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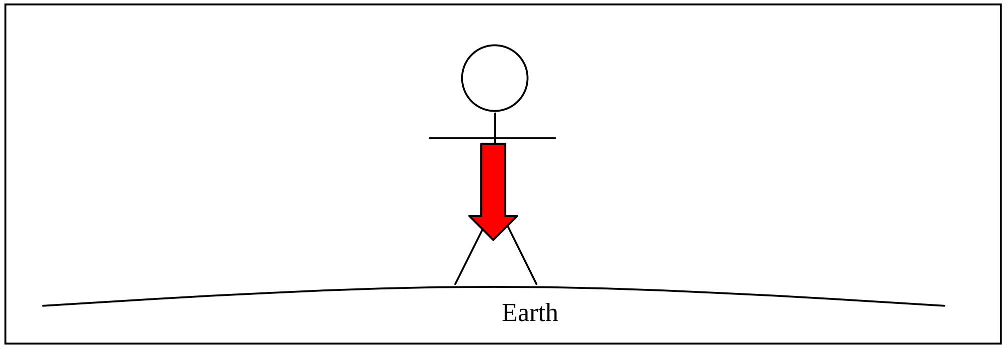

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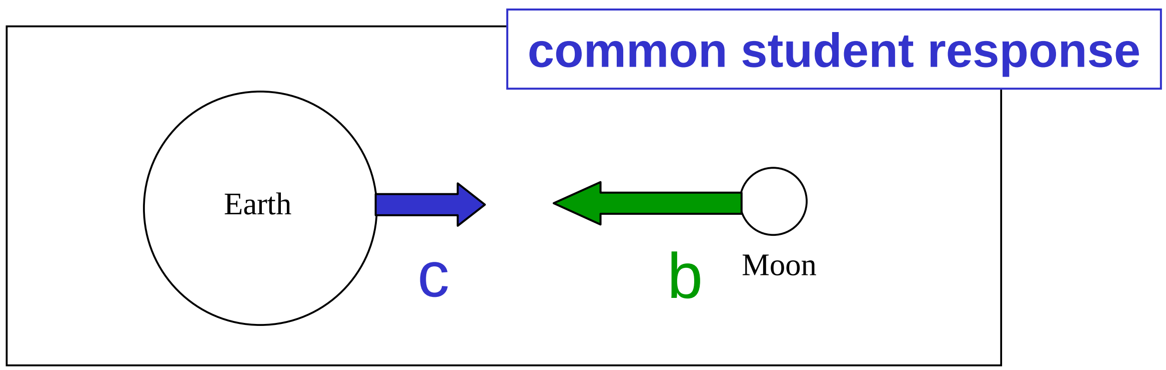

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e) Consider the magnitude of the gravitational force in (b). Write down an algebraic expression for the strength of the force. (Refer to Newton's Universal Law of Gravitation at the top of the previous page.) Use M_e for the mass of the Earth and M_m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

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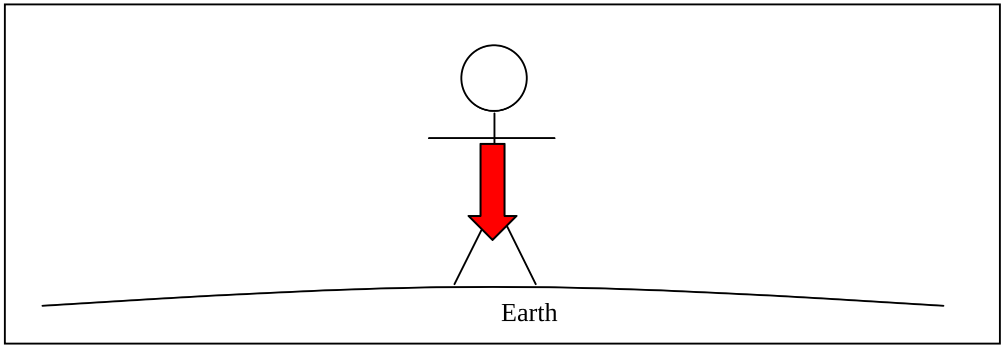

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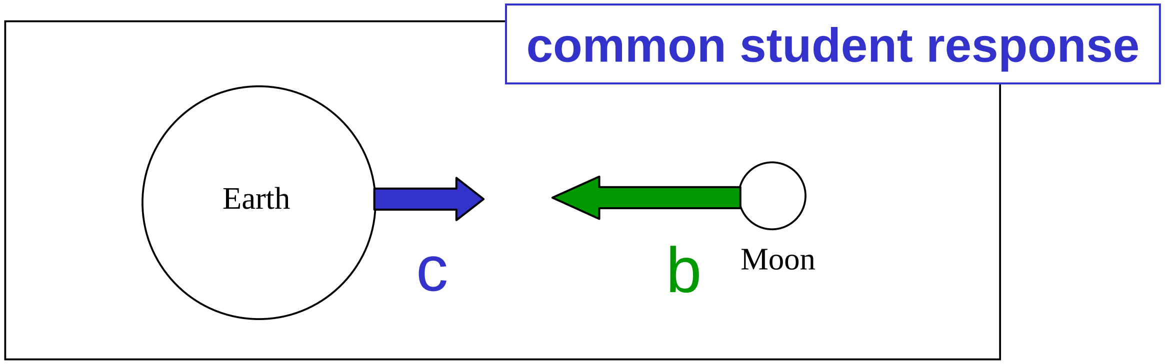

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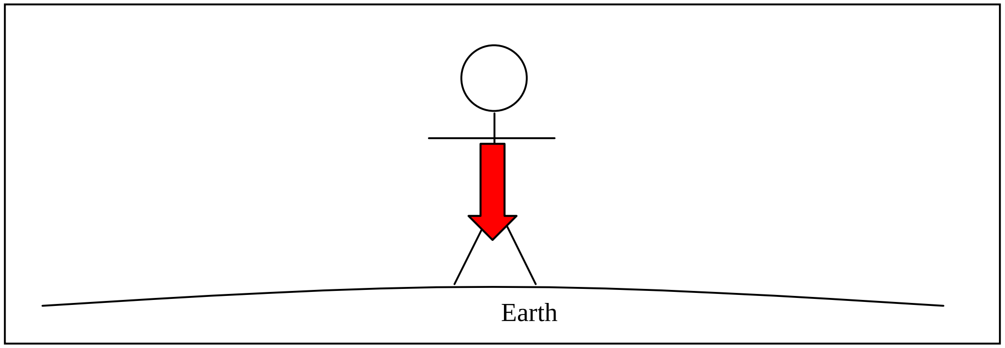

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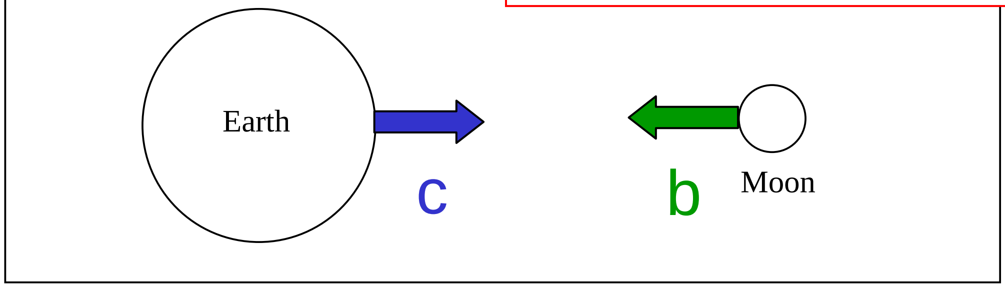
corrected student response



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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.

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

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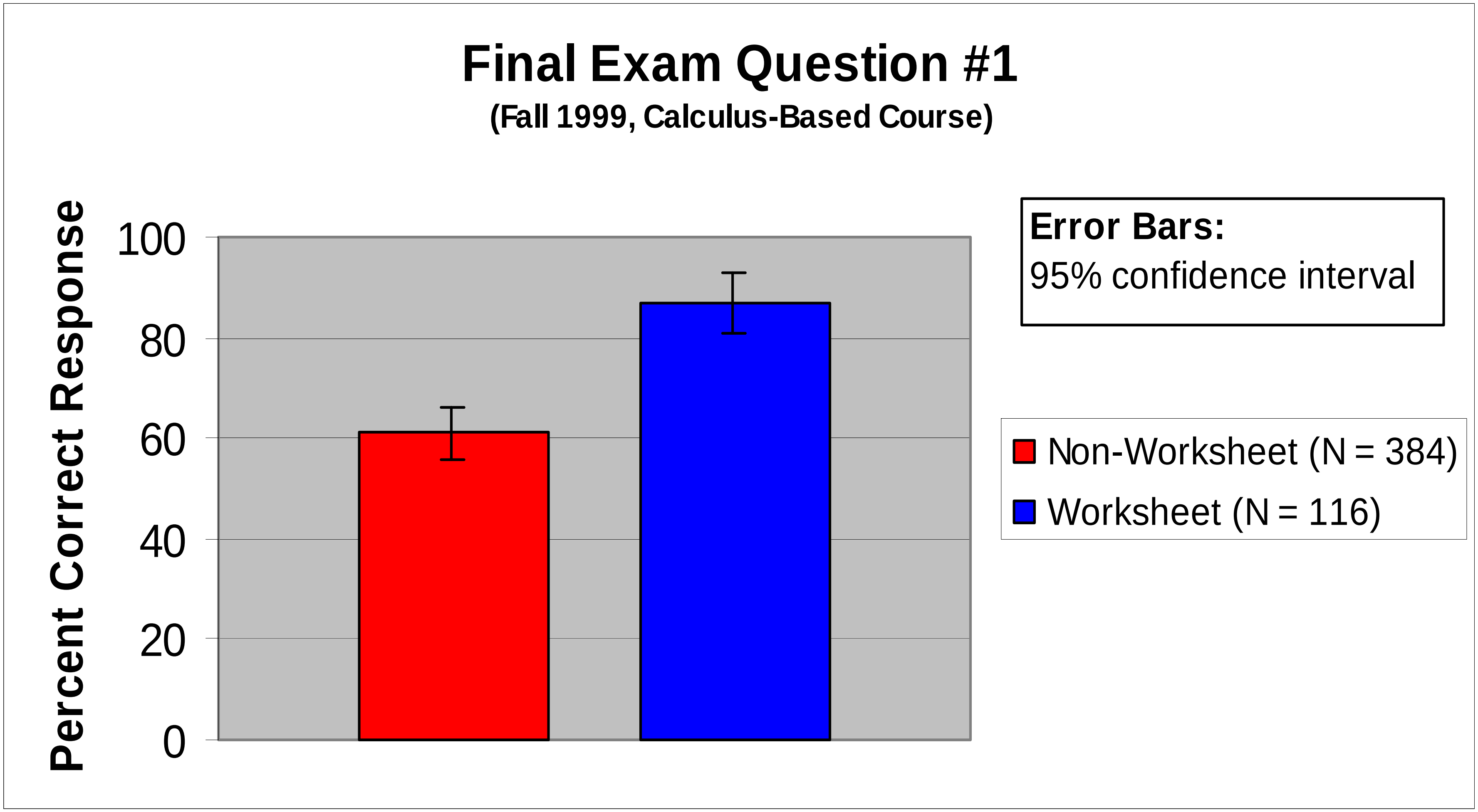
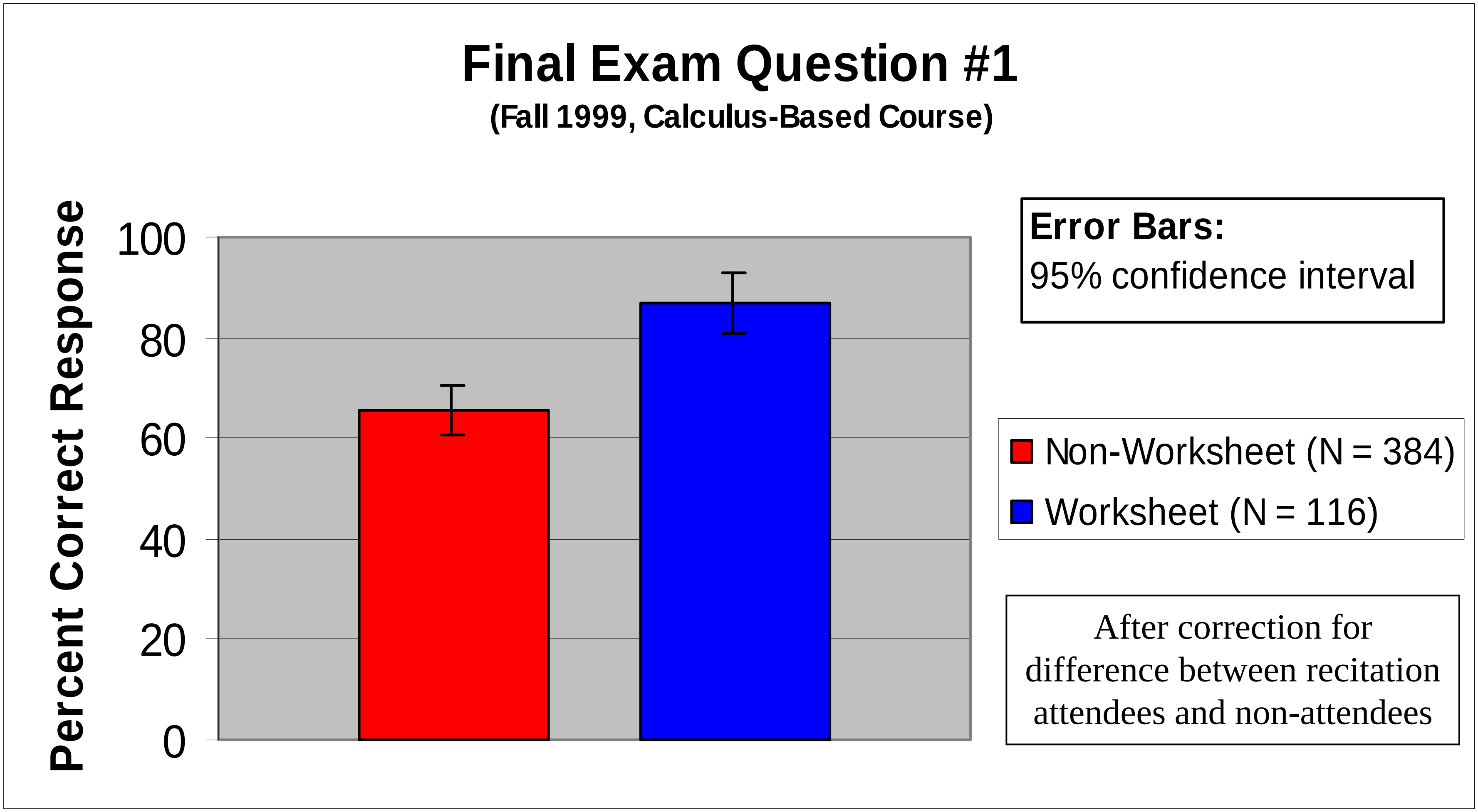

Final Exam Question #1
(Fall 1999, Calculus-Based Course)
Percent Correct Response
100
80
60
40
20
0
Error Bars:
95% confidence interval
Non-Worksheet (N = 384)
Worksheet (N = 116)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Two lead spheres of mass *M* are separated by a distance *r*. They are 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.*

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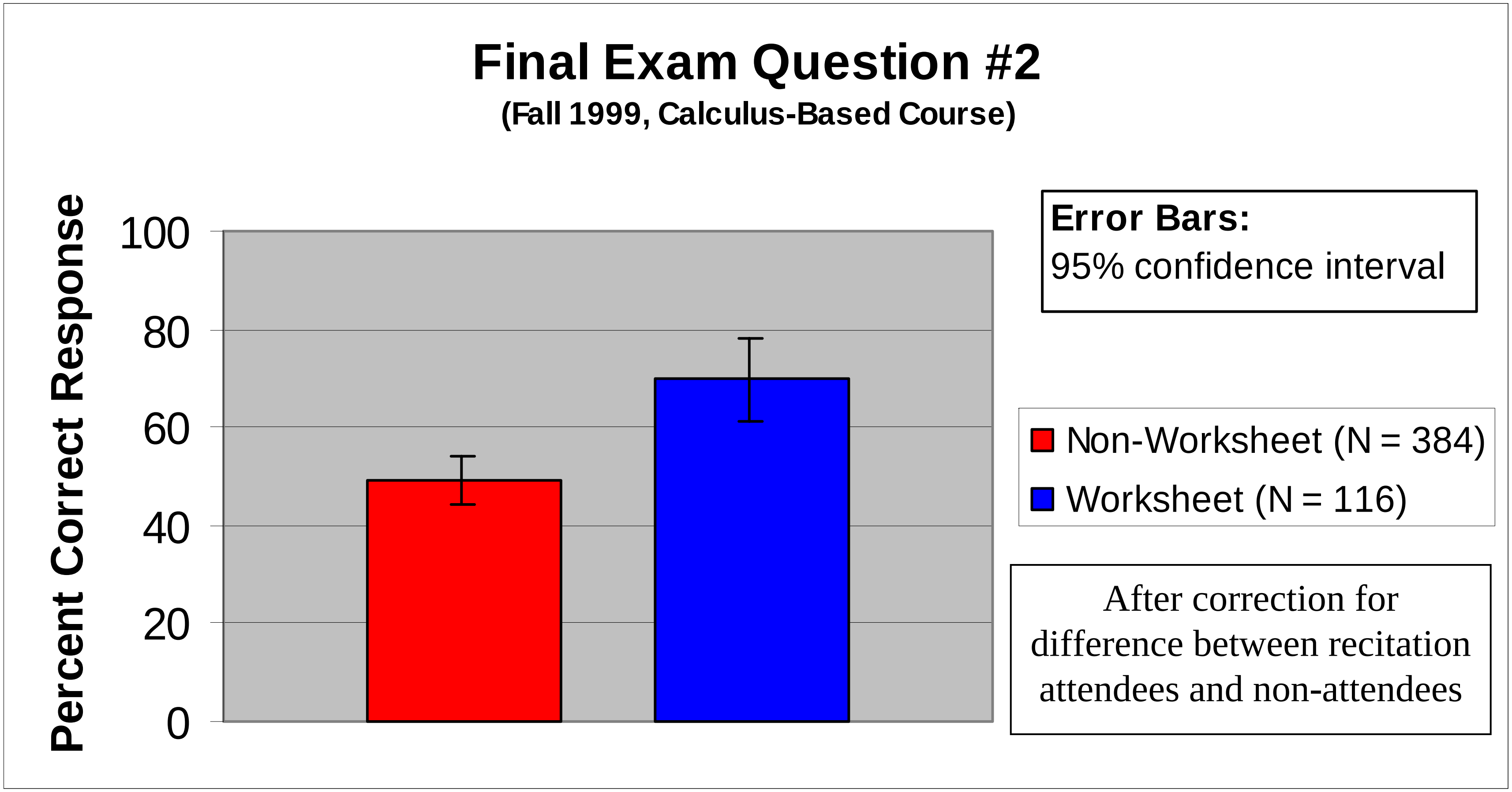
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Outline

1. Physics Education as a Research Problem

Methods of physics education research

2. Research-Based Instructional Methods

Principles and practices

3. Research-Based Curriculum Development

A “model” problem: law of gravitation

4. Recent Work: Student Learning of Thermal Physics

Research and curriculum development

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

Studies of university students in general physics courses have revealed substantial learning difficulties with fundamental concepts, including heat, work, and the first and second laws of thermodynamics:

USA

M. E. Loverude, C. H. Kautz, and P. R. L. Heron (2002);

D. E. Meltzer (2004);

M. Cochran and P. R. L. Heron (2006).

Germany

R. Berger and H. Wiesner (1997)

France

S. Rozier and L. Viennot (1991)

UK

J. W. Warren (1972)

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
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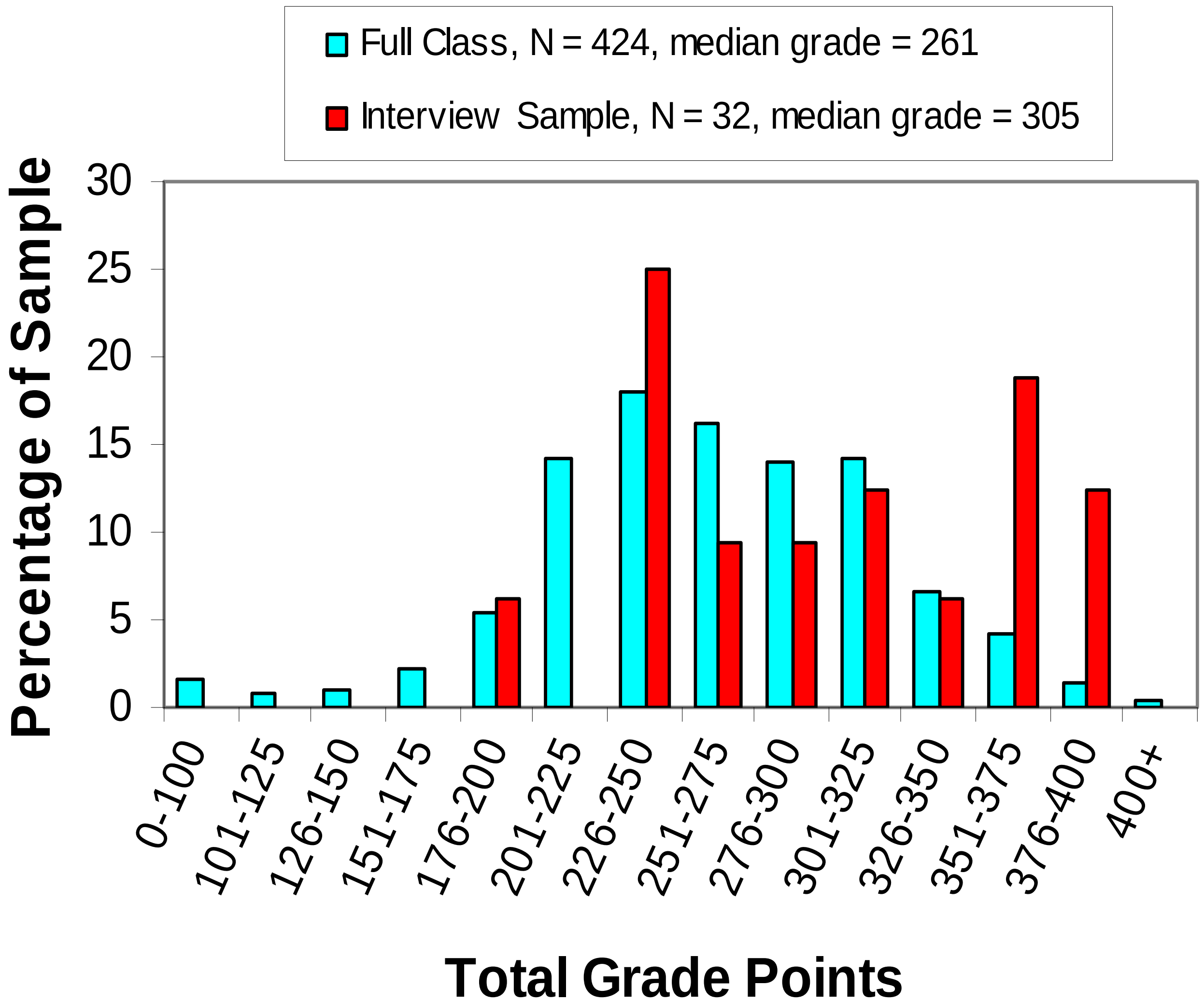
Grade Distributions: Interview Sample vs. Full Class



***Interview Sample*:**

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

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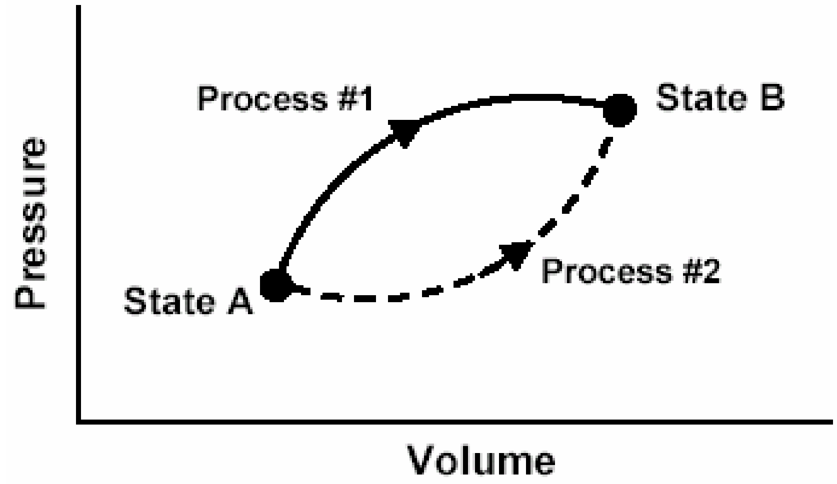

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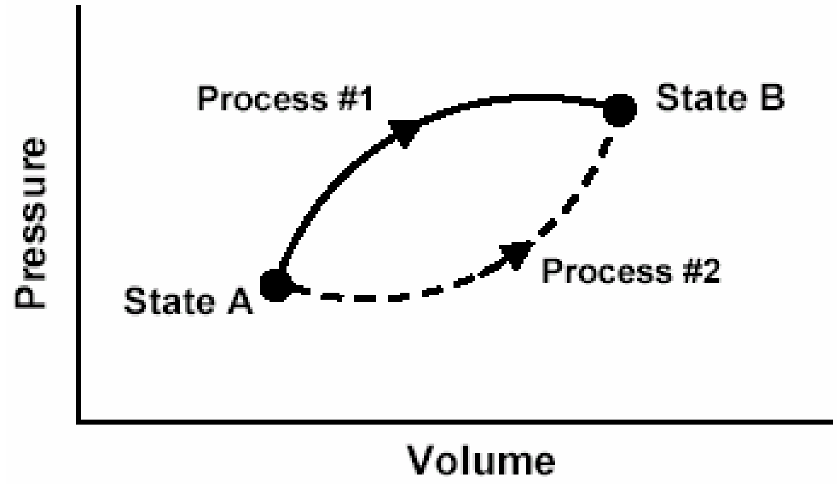

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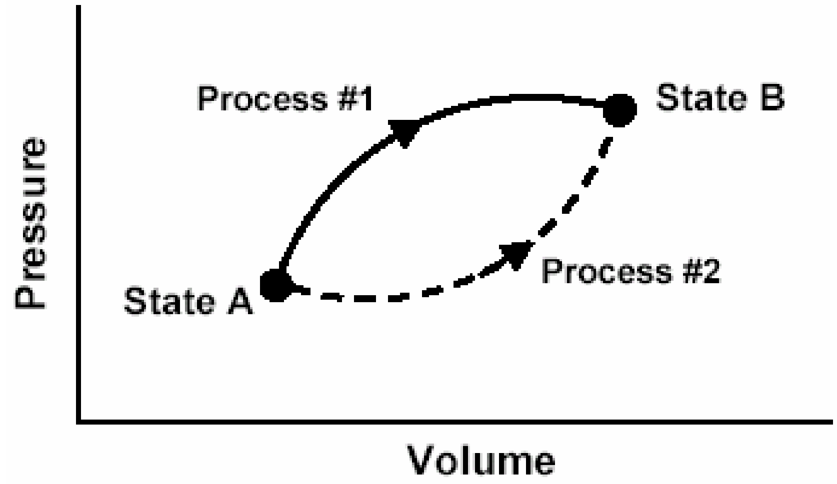

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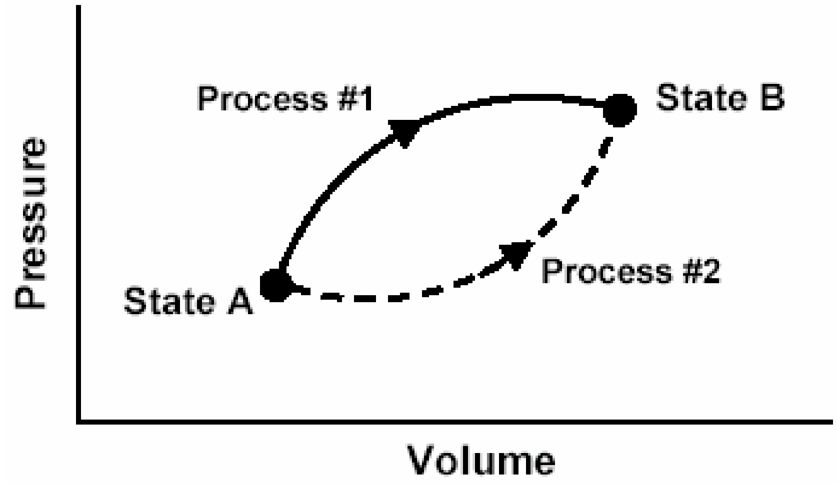

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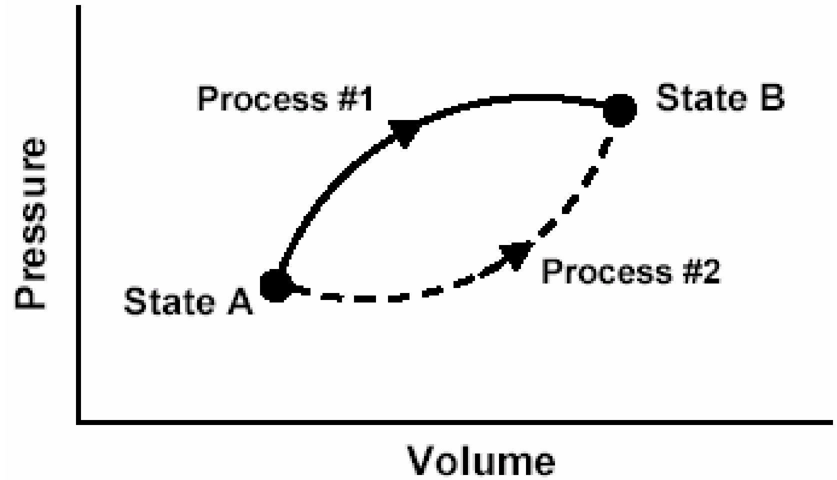

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Responses to Diagnostic Question #1

(Work question)

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**	**2002** **Introductory Physics** **(Post-test)** **Interview Sample** **(*N*=32)**	**2004** **Thermal Physics** **(Pretest)** **(*N*=19)**
$W_1 > W_2$			
$W_1 = W_2$			
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Responses to Diagnostic Question #1
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$W_1 = W_2$	**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

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Confusion with mechanical work done by conservative forces?

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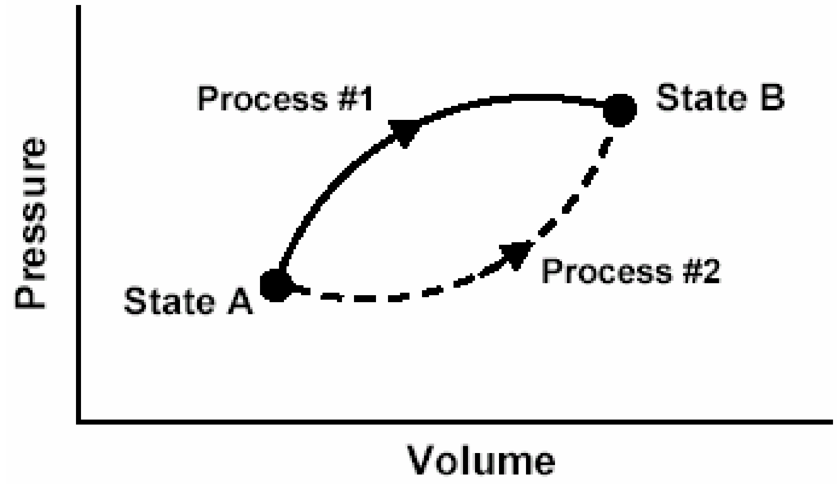

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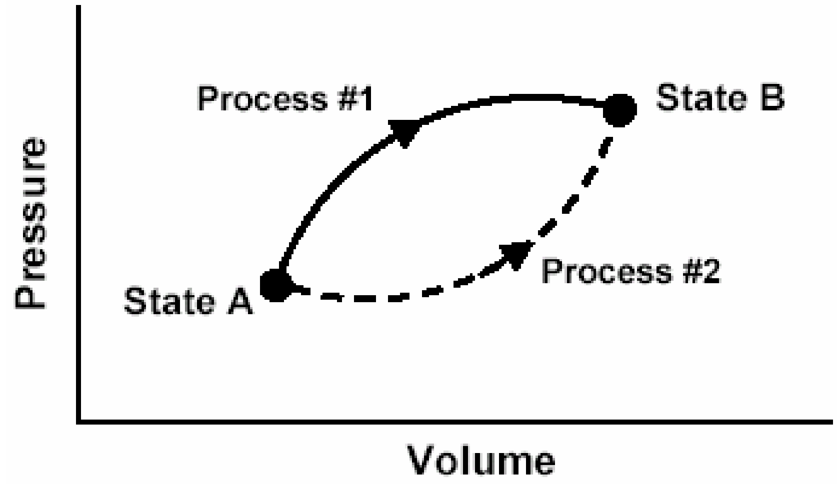

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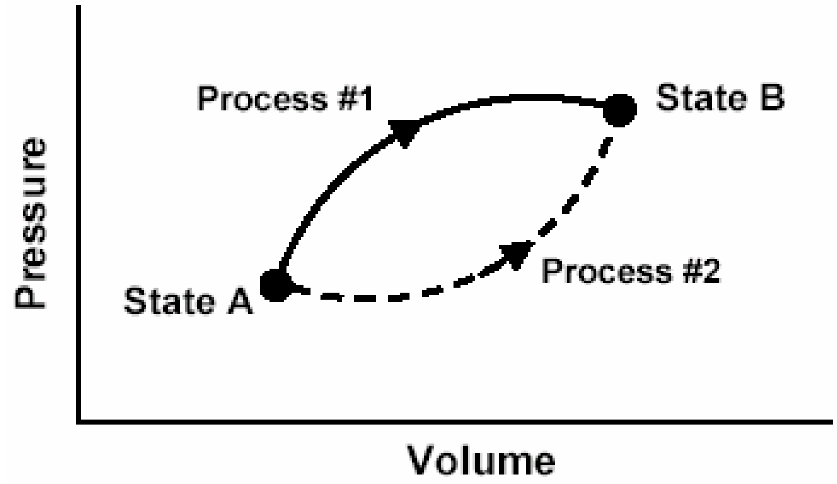
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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



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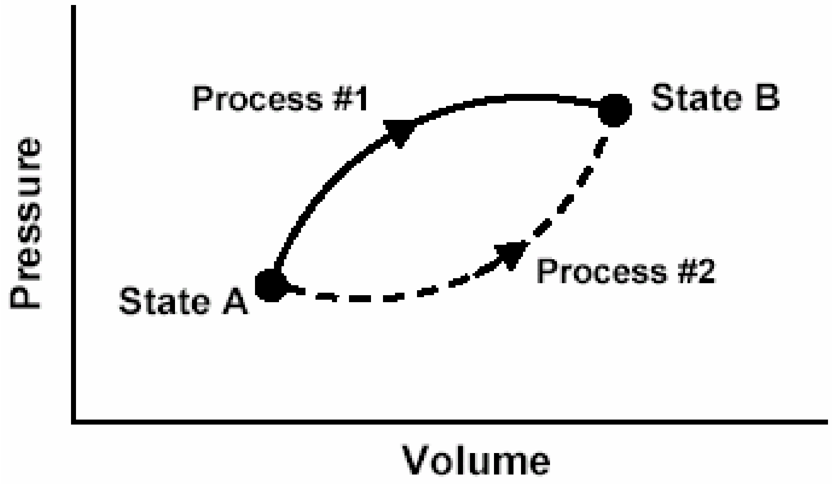
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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



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Responses to Diagnostic Question #2

(Heat question)

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$Q_1 > Q_2$			
$Q_1 = Q_2$			
$Q_1 < Q_2$			

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)
$Q_1 > Q_2$			
$Q_1 = Q_2$			
$Q_1 < Q_2$			

Responses to Diagnostic Question #2
(Heat question)

$Q_1 > Q_2$			
[Correct answer]			

Responses to Diagnostic Question #2
(Heat question)

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	2002 Introductory Physics (Post-test) Interview Sample (*N*=32)	2003 Thermal Physics (Pretest) (*N*=14)
$Q_1 > Q_2$	45%	34%	35%

Responses to Diagnostic Question #2

(Heat question)

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	2002 Introductory Physics (Post-test) Interview Sample (*N*=32)	2003 Thermal Physics (Pretest) (*N*=14)
$Q_1 > Q_2$	45%	34%	35%
Correct or partially correct explanation	11%	19%	30%

Responses to Diagnostic Question #2

(Heat question)

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	2002 Introductory Physics (Post-test) Interview Sample (*N*=32)	2004 Thermal Physics (Pretest) (*N*=19)
$Q_1 > Q_2$	**45%**	**34%**	**30%**
Correct or partially correct explanation	**11%**	**19%**	**30%**

Responses to Diagnostic Question #2

(Heat question)

	1999-2001 Introductory Physics (Post-test) Written Sample (N=653)	**2002** Introductory Physics (Post-test) Interview Sample (N=32)	**2004** Thermal Physics (Pretest) (N=19)
$Q_1 > Q_2$	**45%**	**34%**	**30%**
Correct or partially correct explanation	**11%**	**19%**	**30%**

Performance of upper-level students 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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*Even **after** instruction, many students (40-80%):*

- believe that heat and/or work are state functions independent of process

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

Cyclic Process Questions

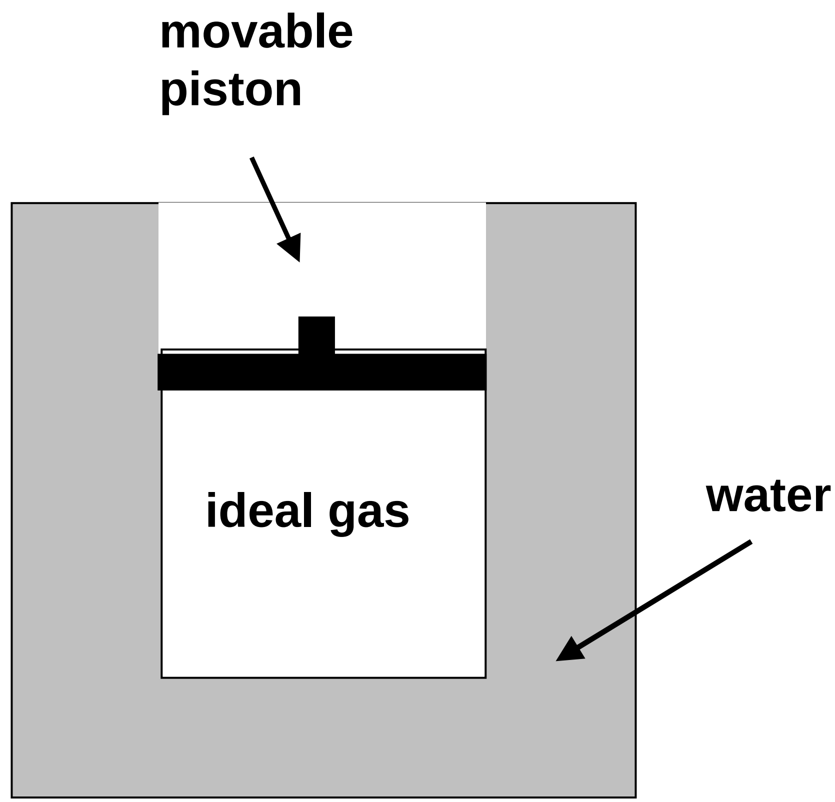
A fixed quantity of ideal gas is contained within a metal cylinder that is sealed with a movable, frictionless, insulating piston.

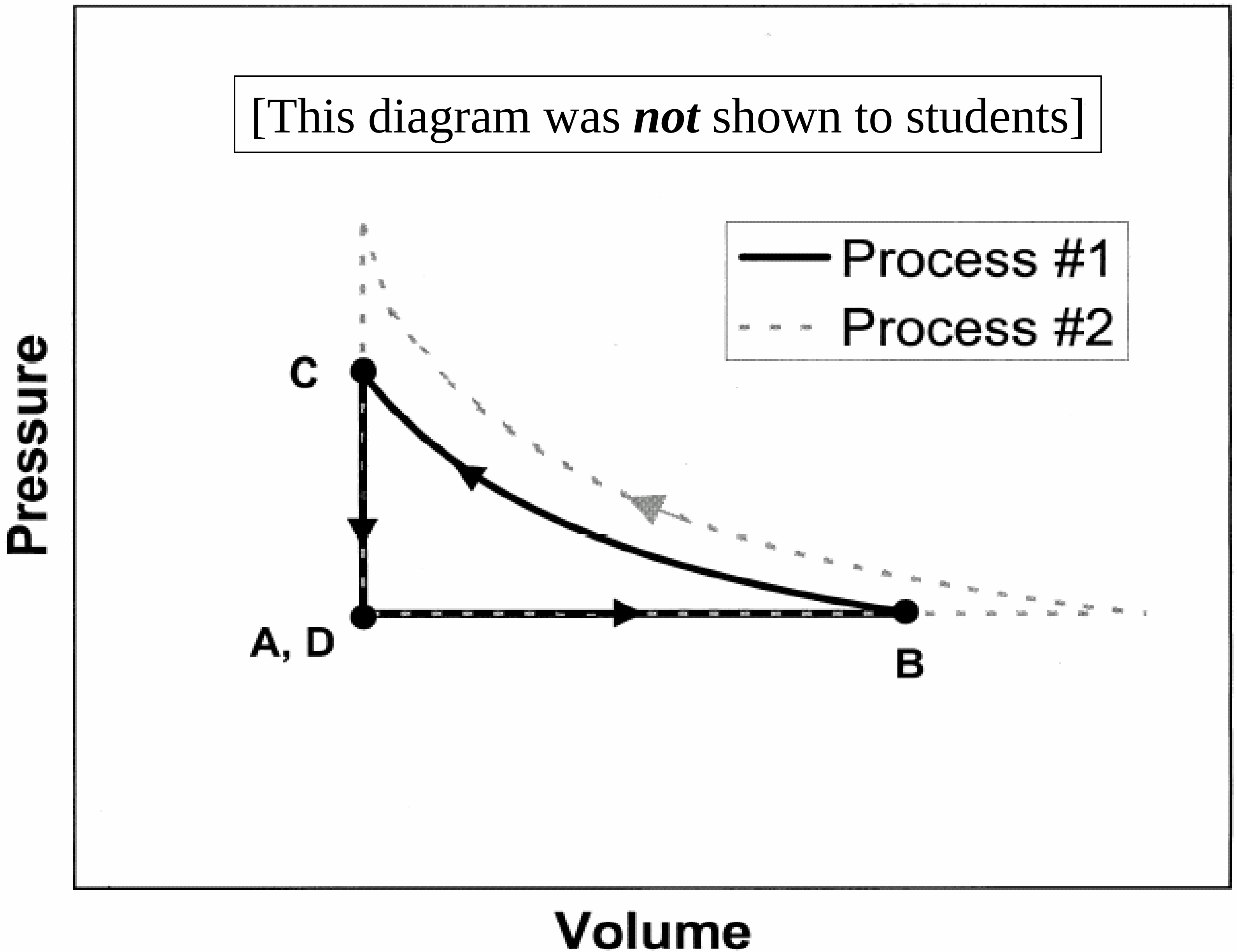
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

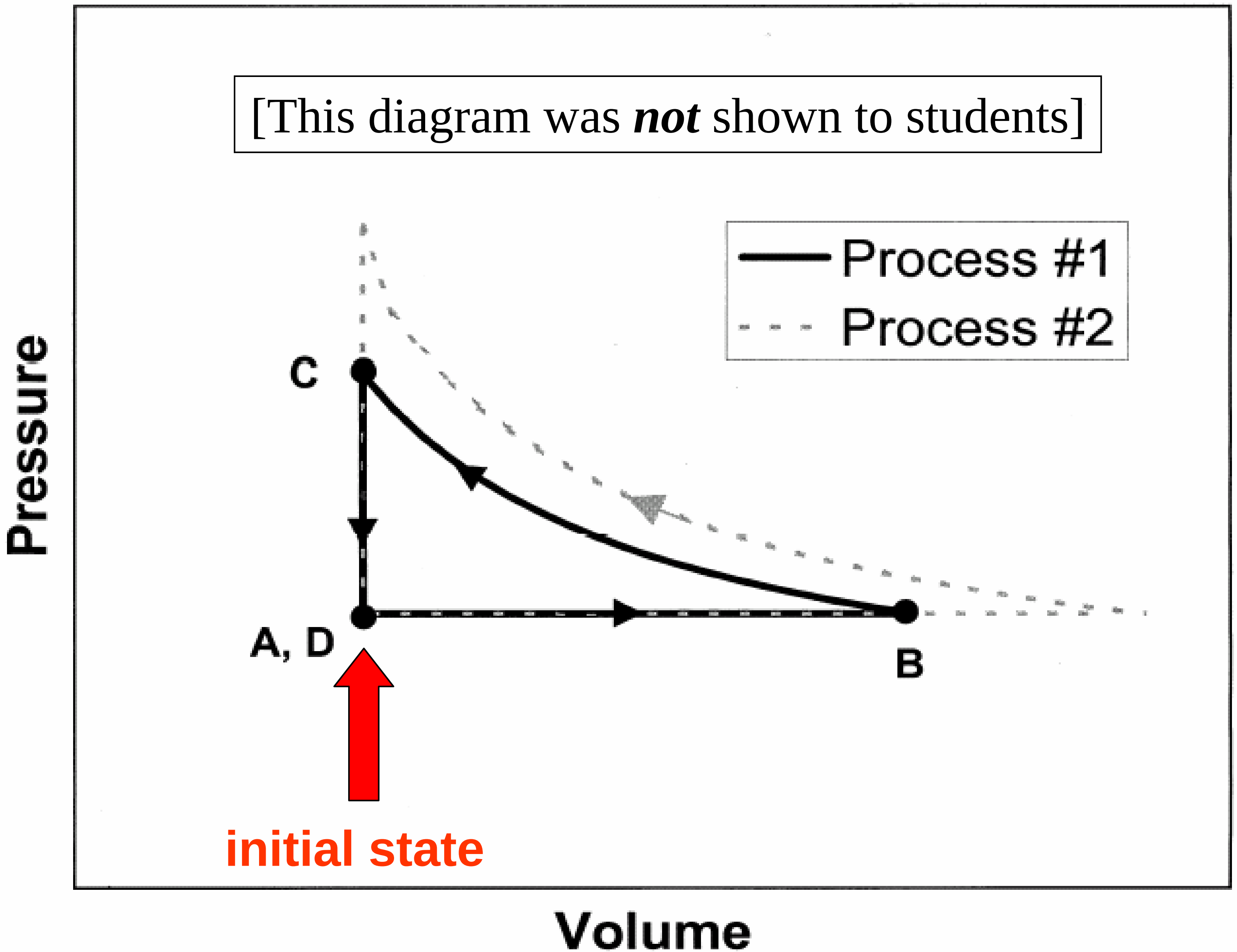
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature

Time *A*

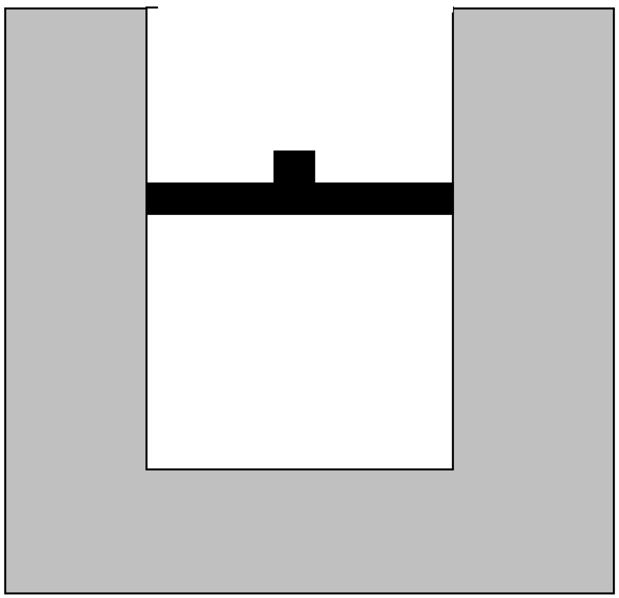
Entire system at room temperature.

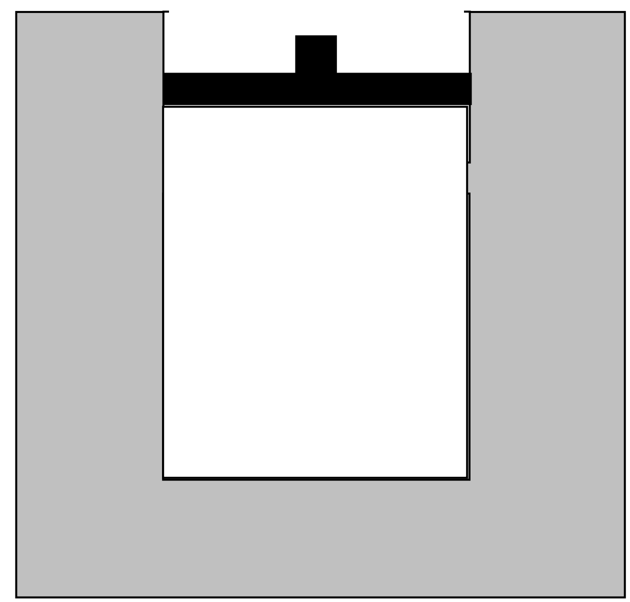



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

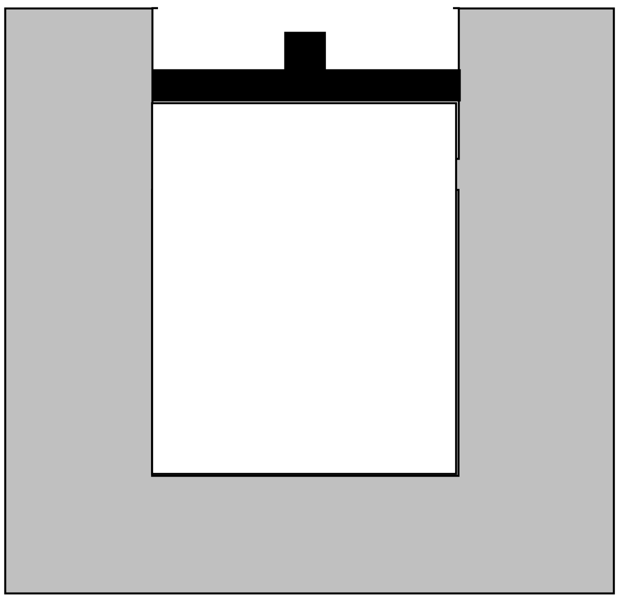

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
initial state
Pressure
Volume

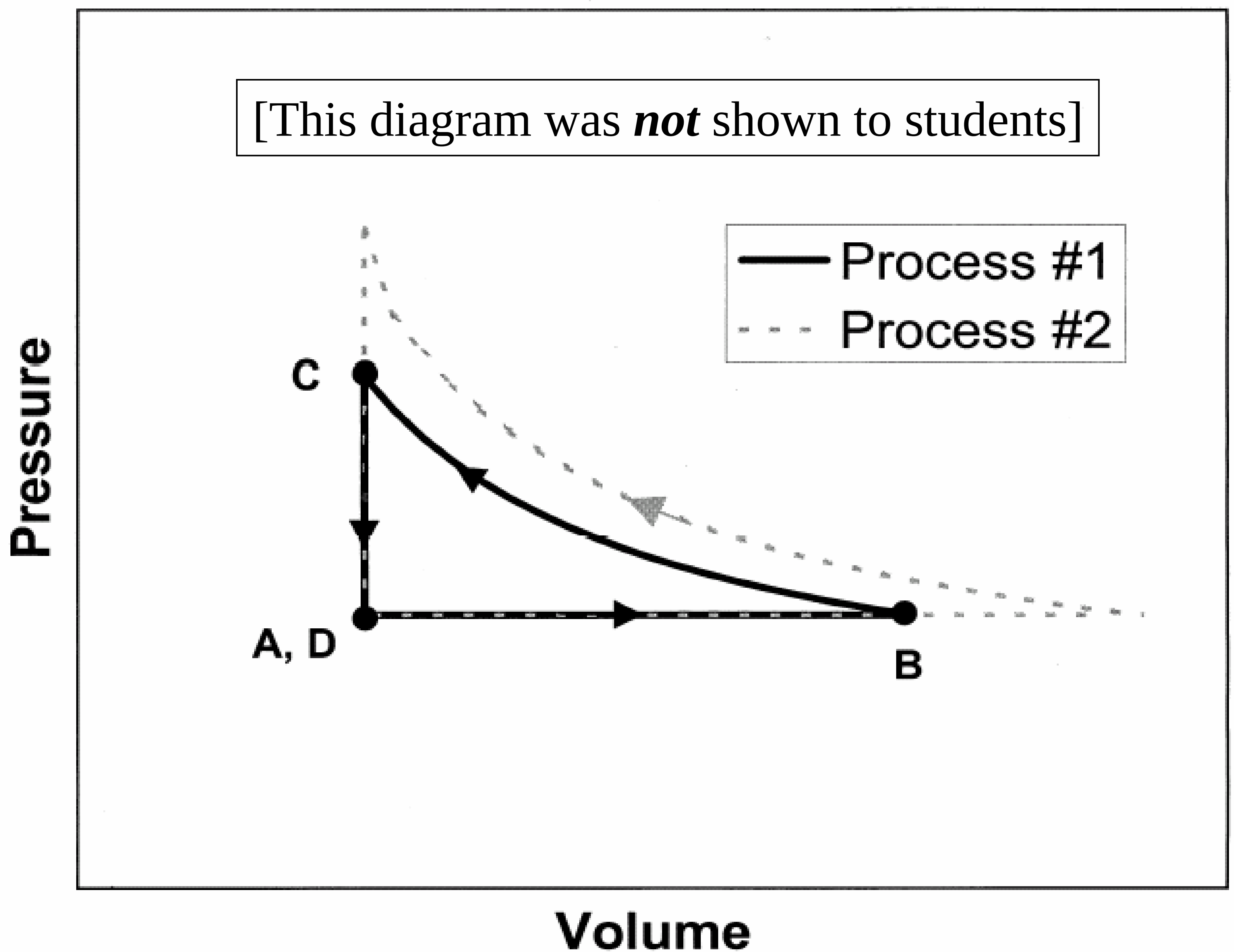
Beginning at time *A*, the water container is gradually heated, and the piston *very slowly* moves upward.

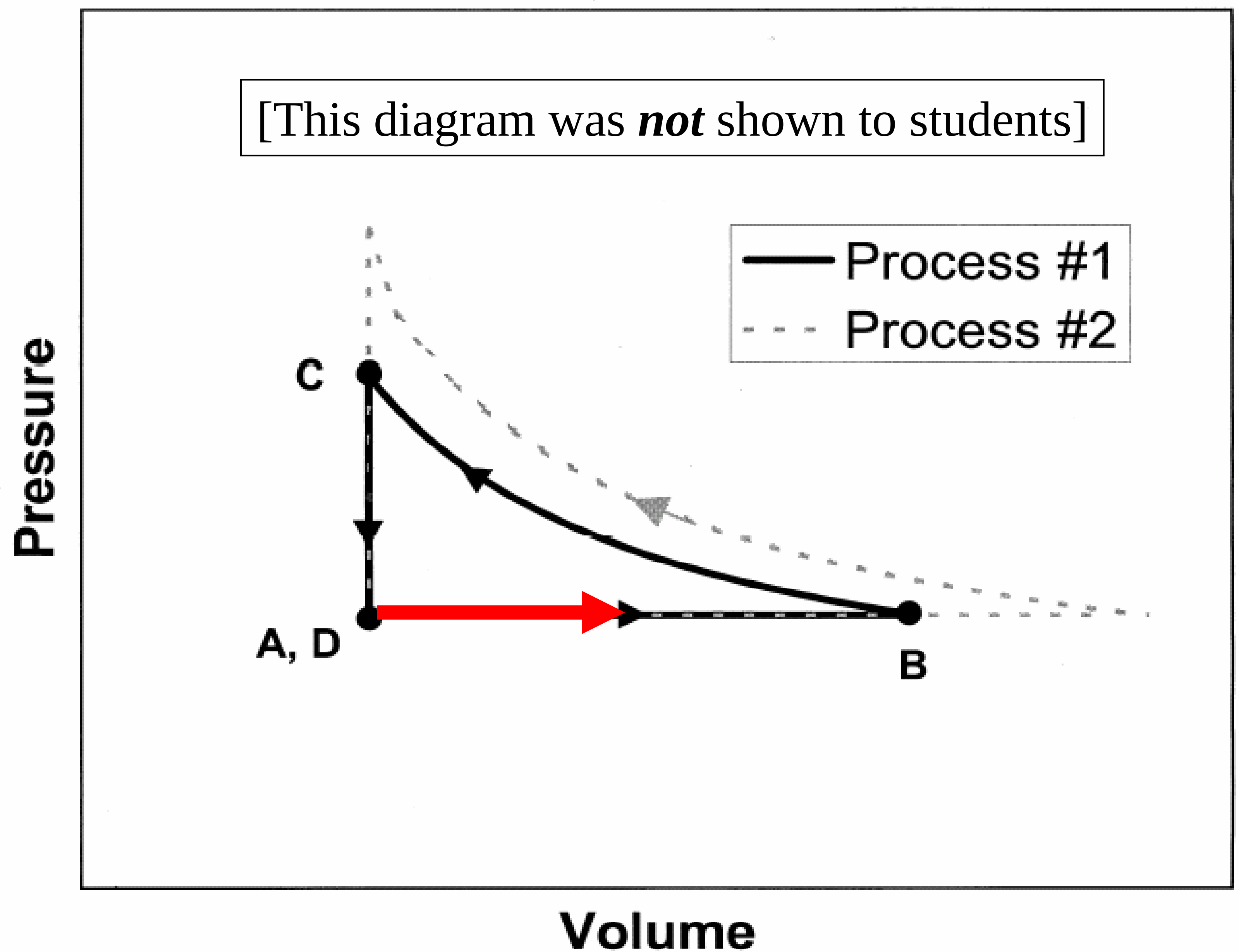




At time ***B*** the heating of the water stops, and the piston stops moving




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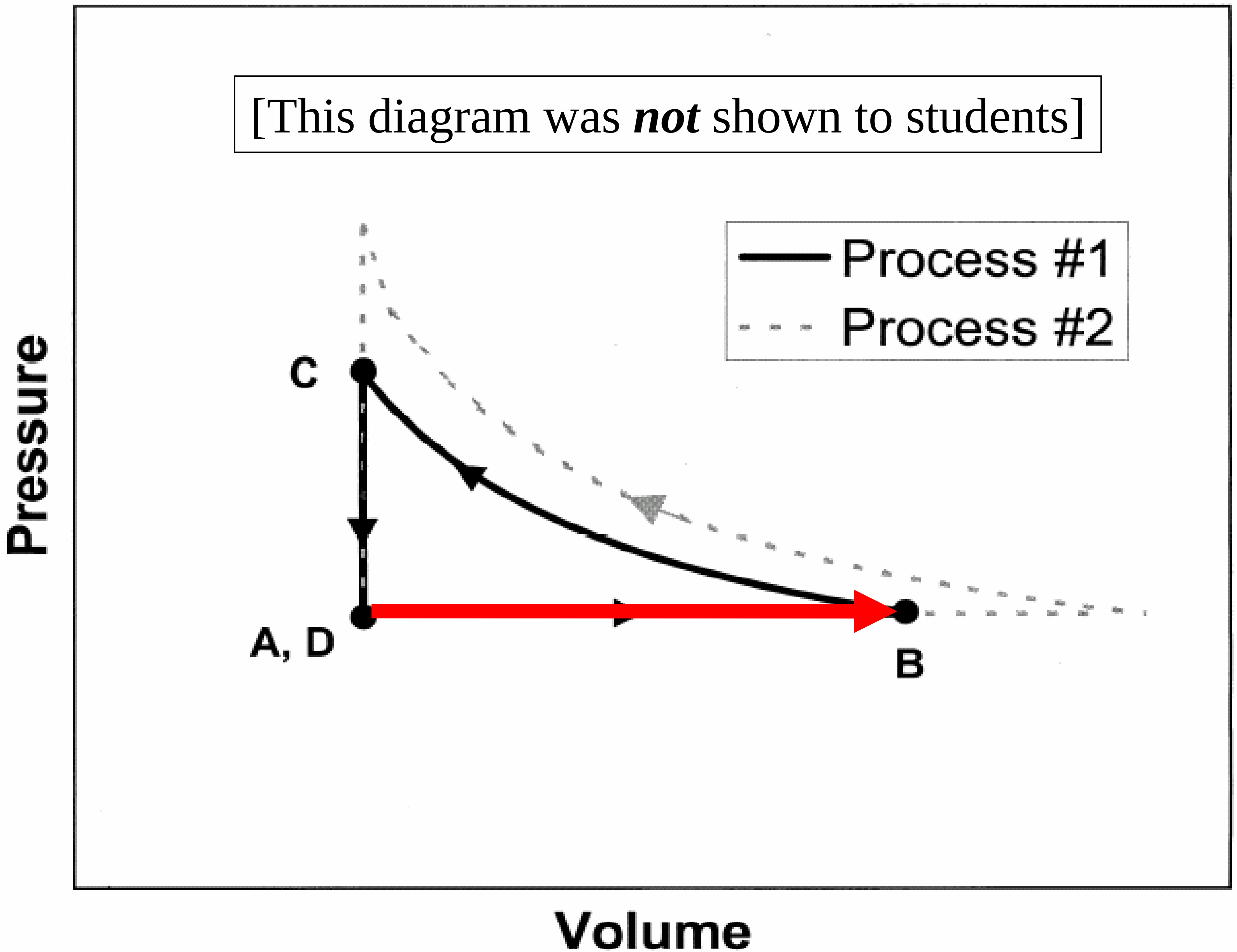
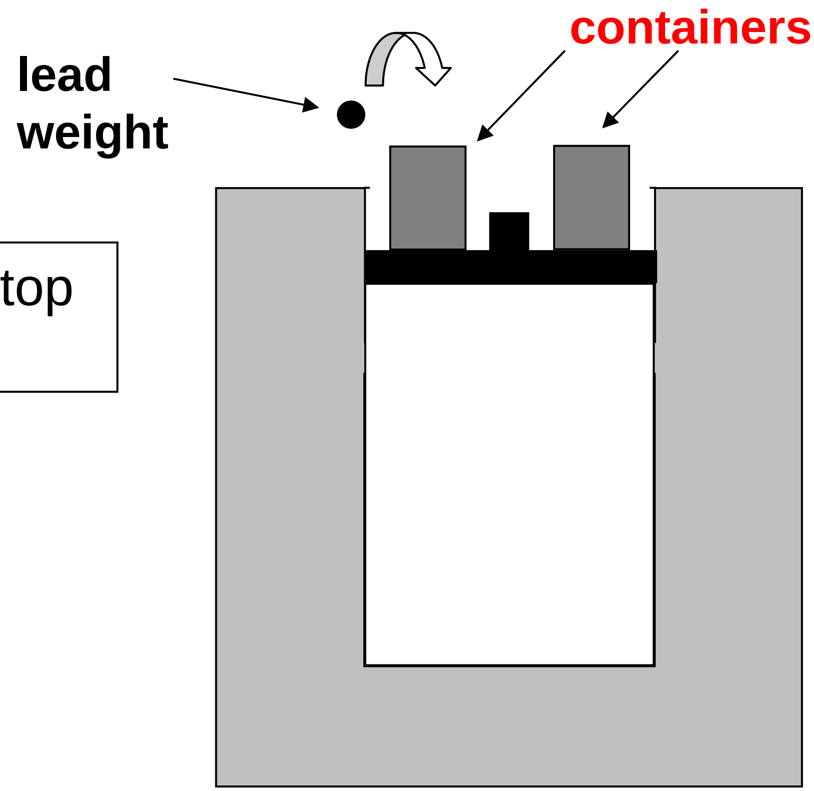
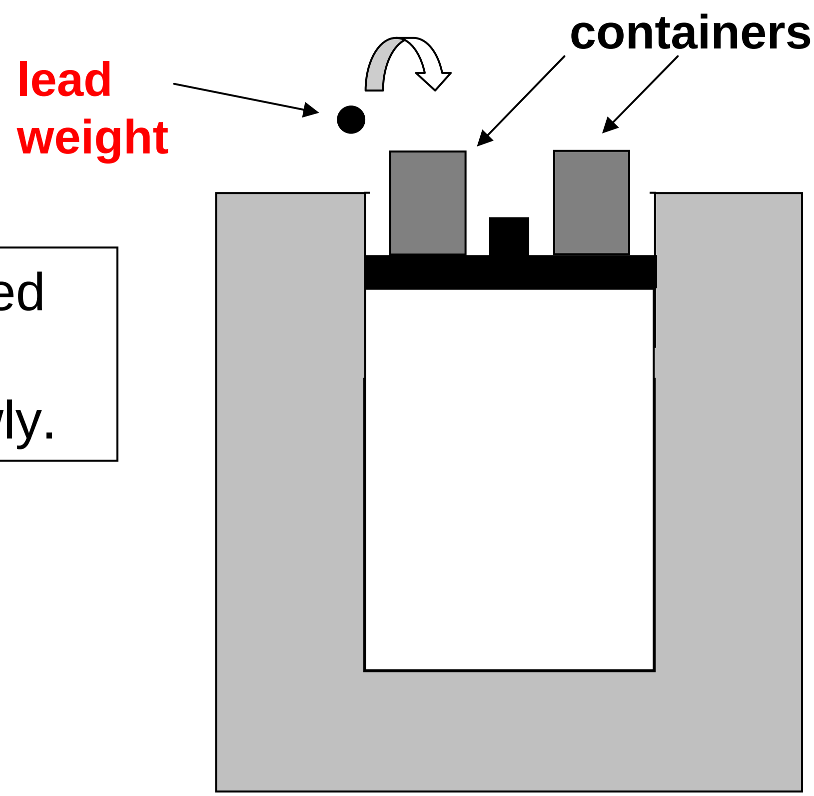
Process #1
Process #2
C
A, D
B
Pressure
Volume

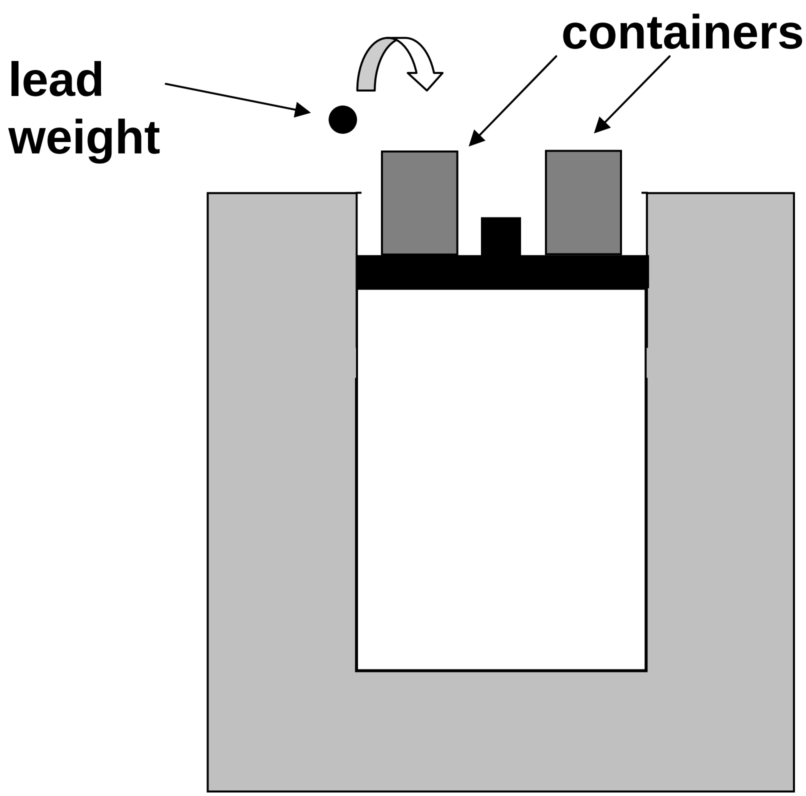

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

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

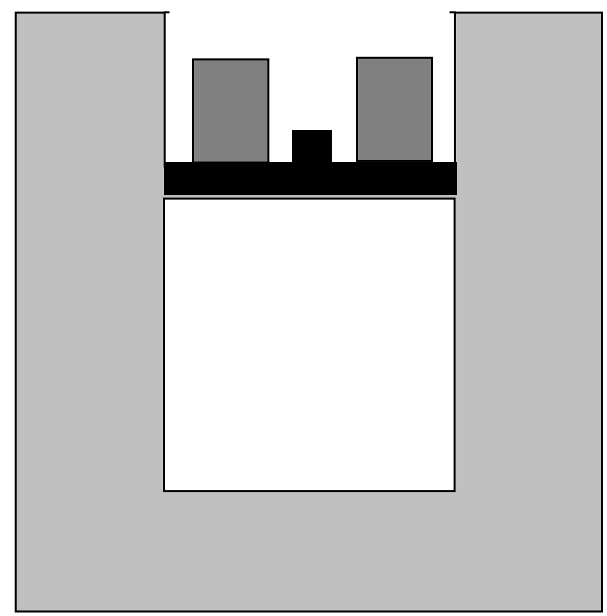


Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly.

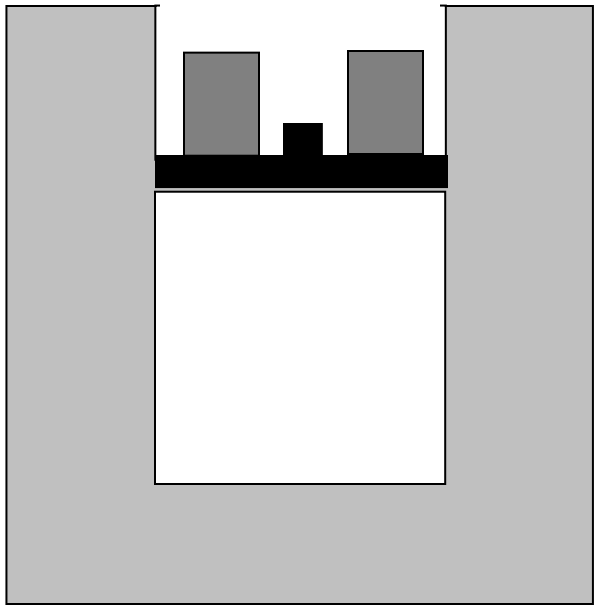




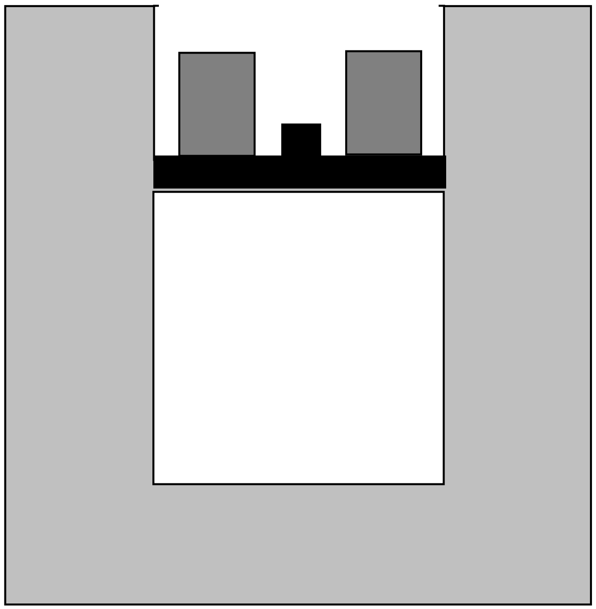
lead
weight
containers

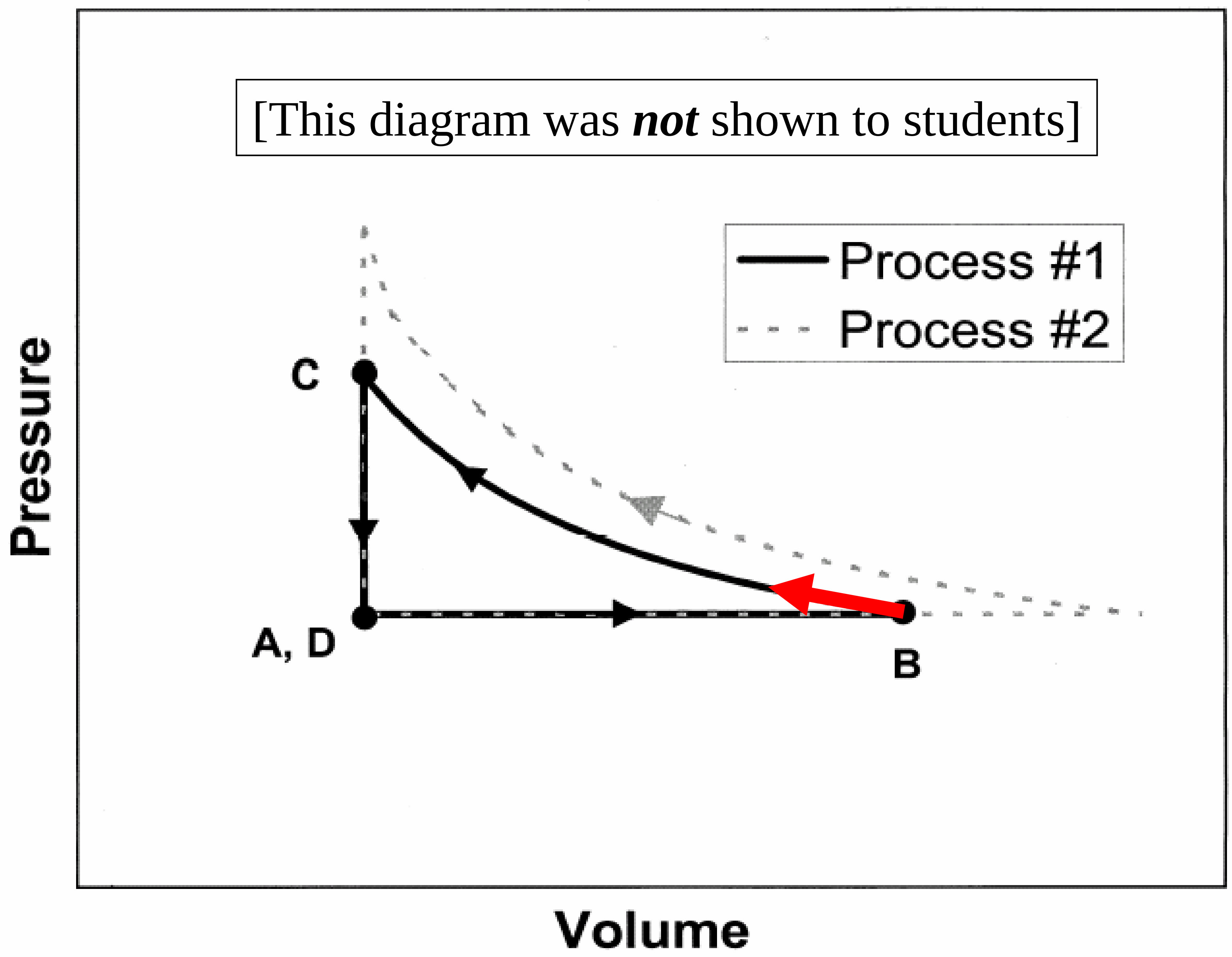


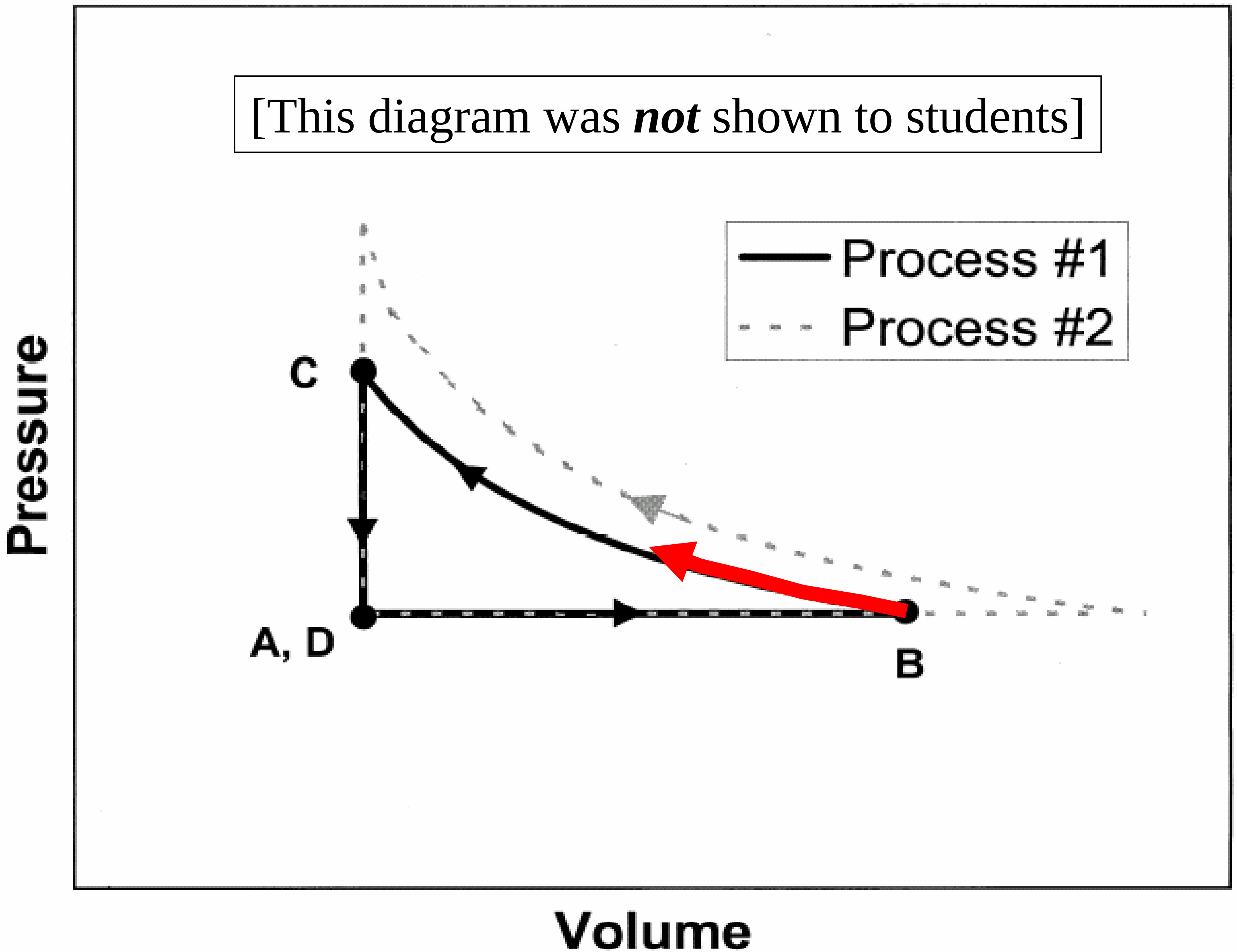
While this happens the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*.



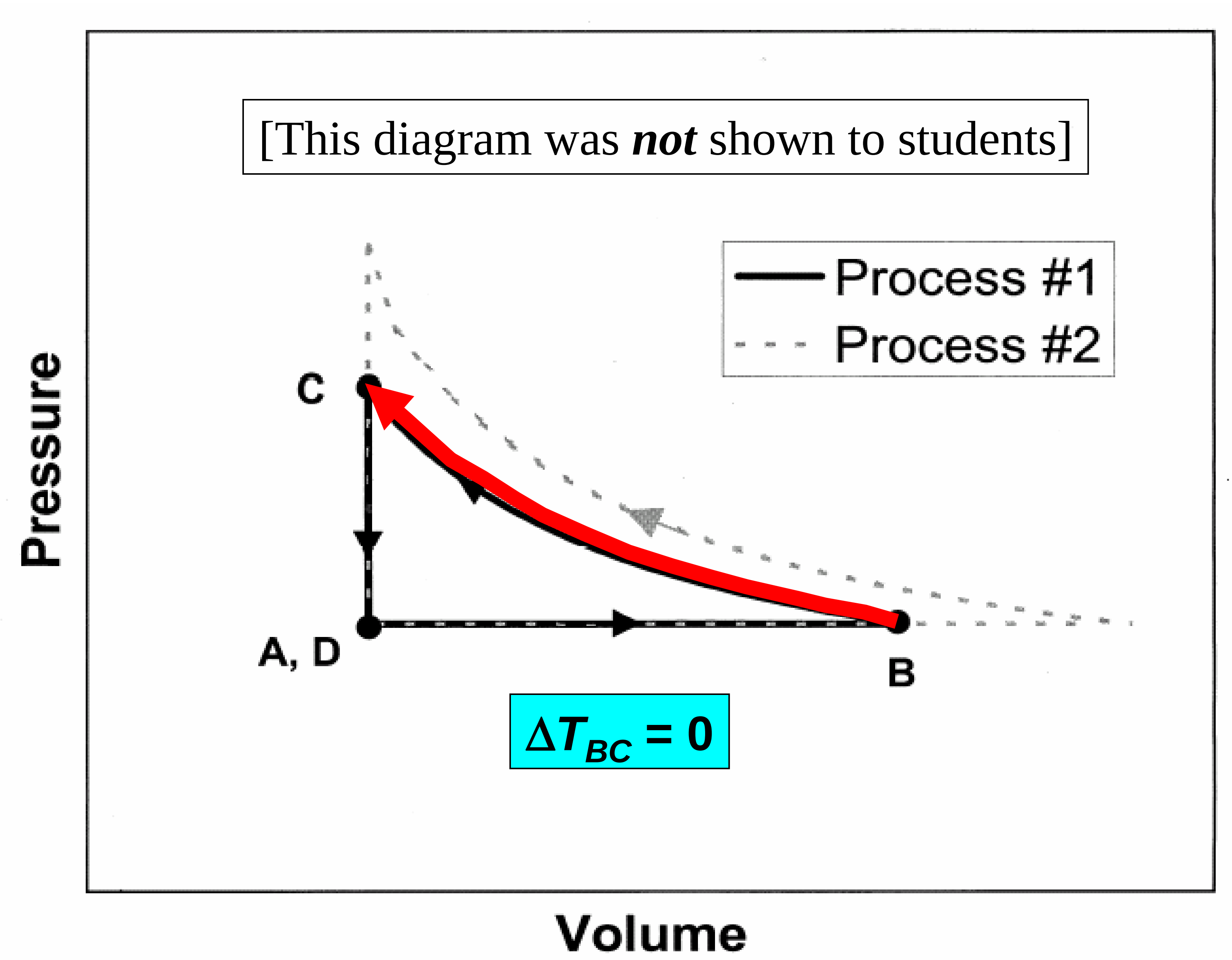
At time ***C*** we stop adding lead weights to the container and the piston stops moving. The piston is now at exactly the same position it was at time ***A*** .




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

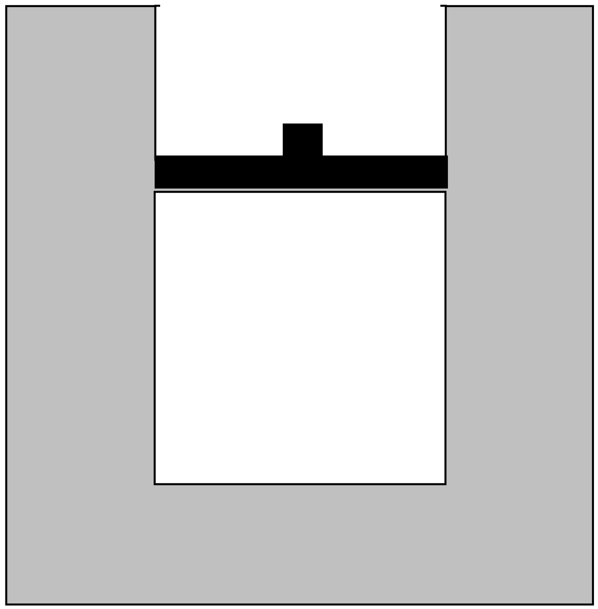


[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

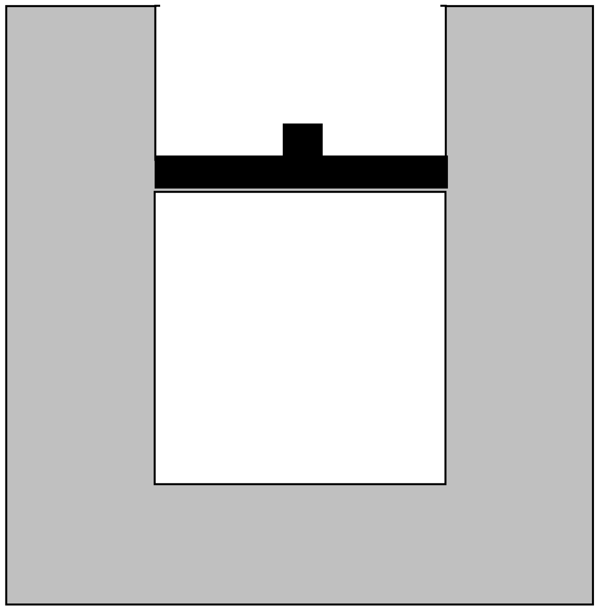


[This diagram was ***not*** shown to students]
Process #1
Process #2
C
A, D
B
$\Delta T_{BC} = 0$
Pressure
Volume

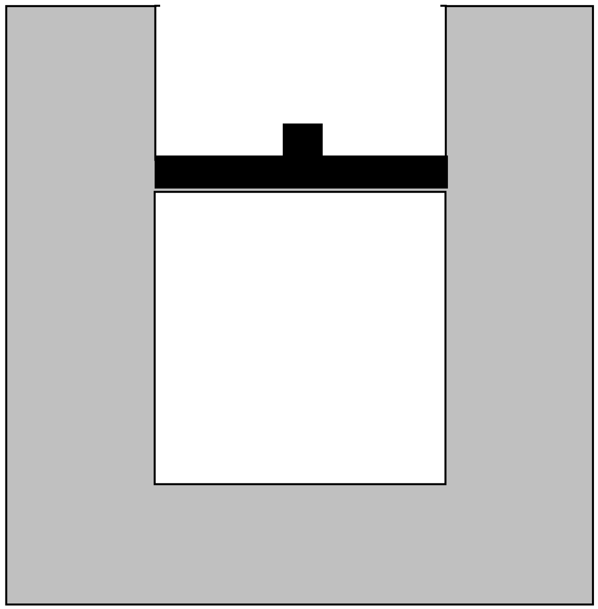
Now, the piston is locked into place so it *cannot move*, and the weights are removed from the piston.



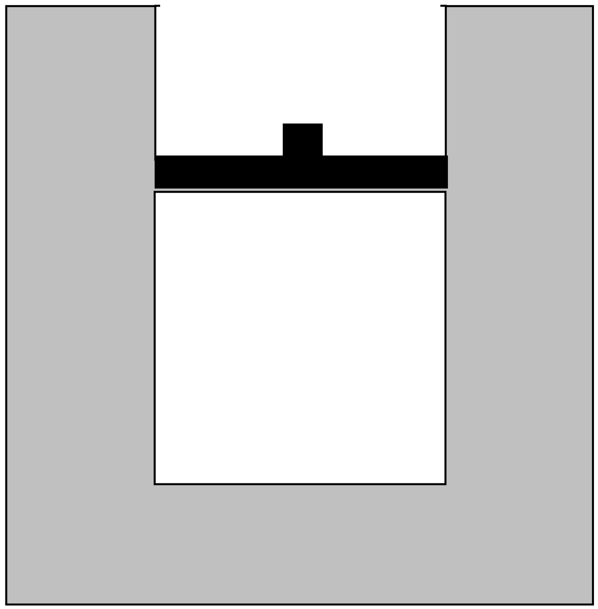
The system is left to sit in the room for many hours.

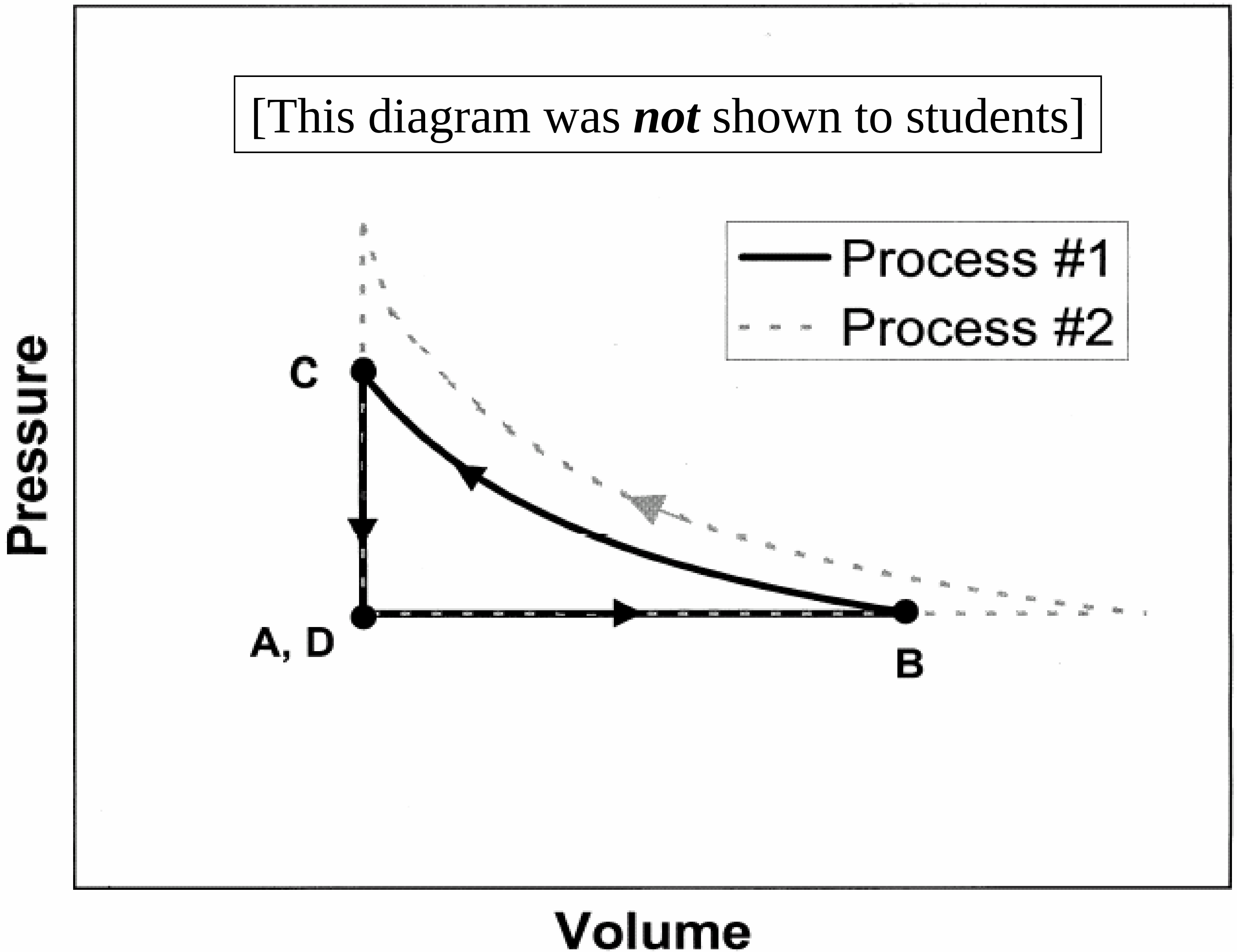


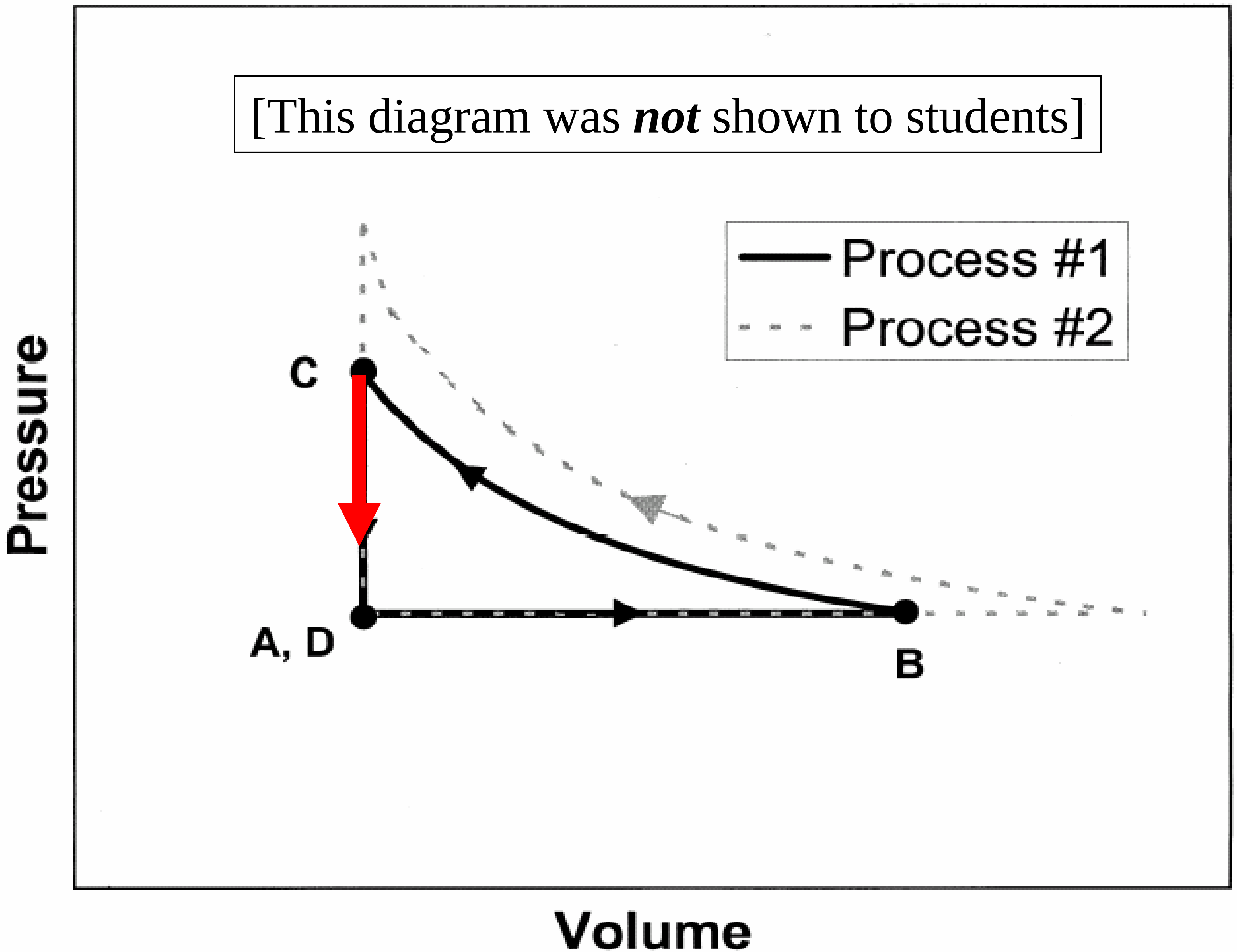
Eventually the entire system cools back down to the same room temperature it had at time ***A***.

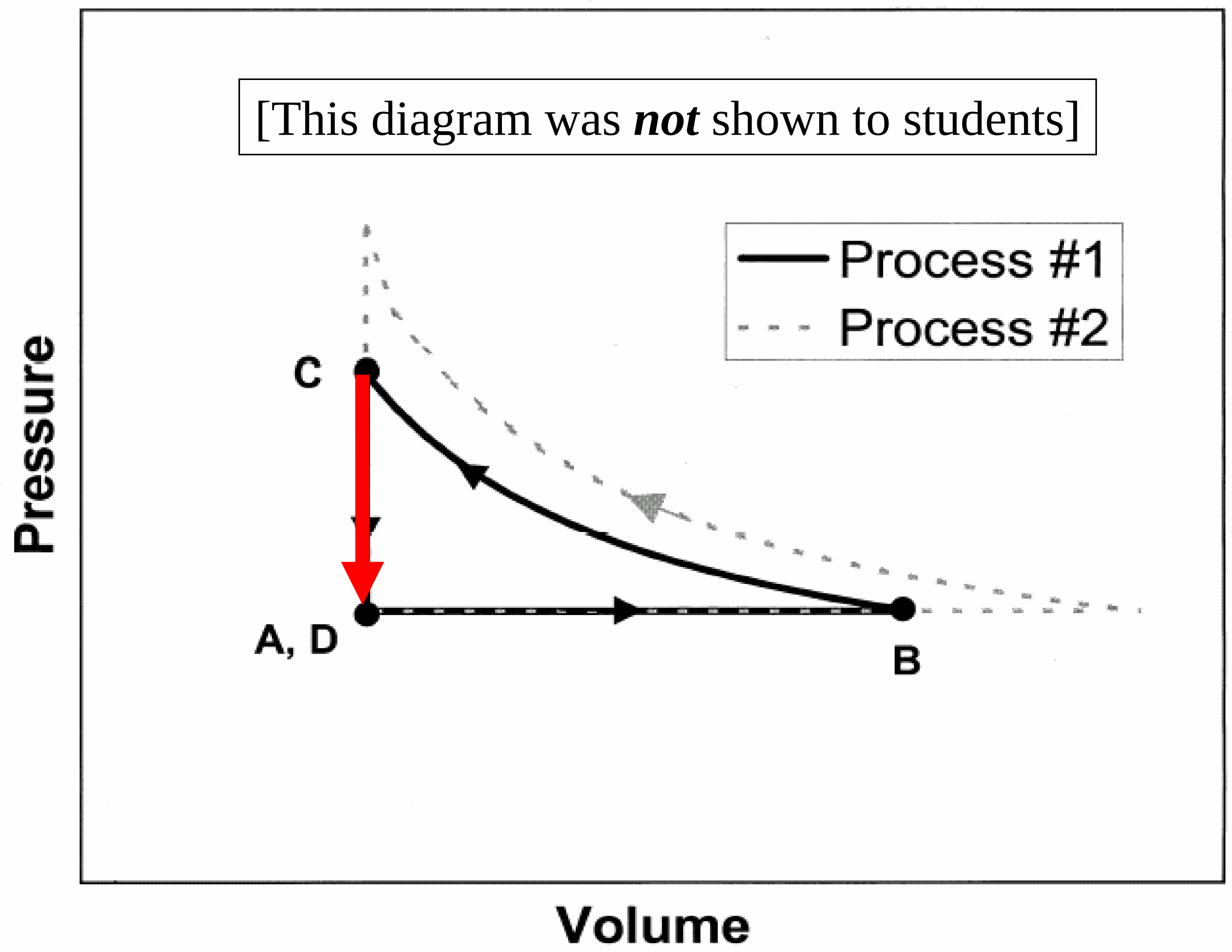


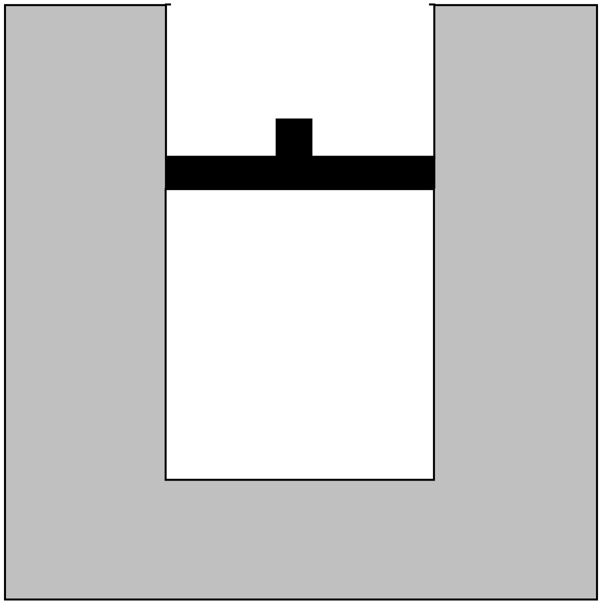
After cooling is complete, it is time ***D.***




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


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

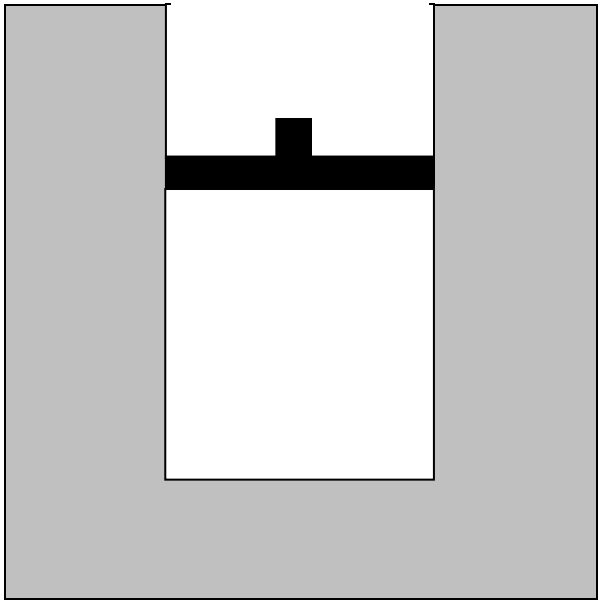

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume



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

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

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



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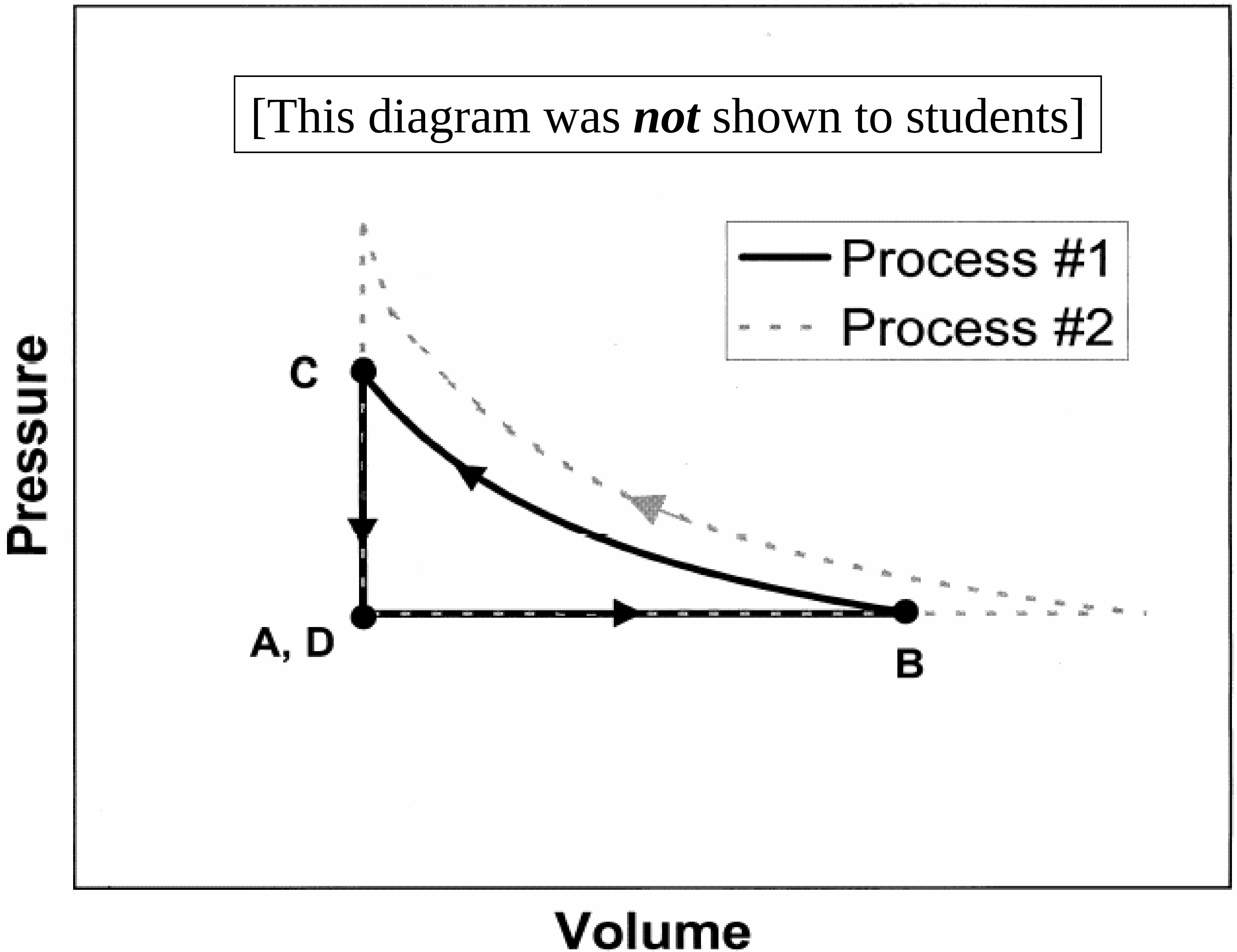
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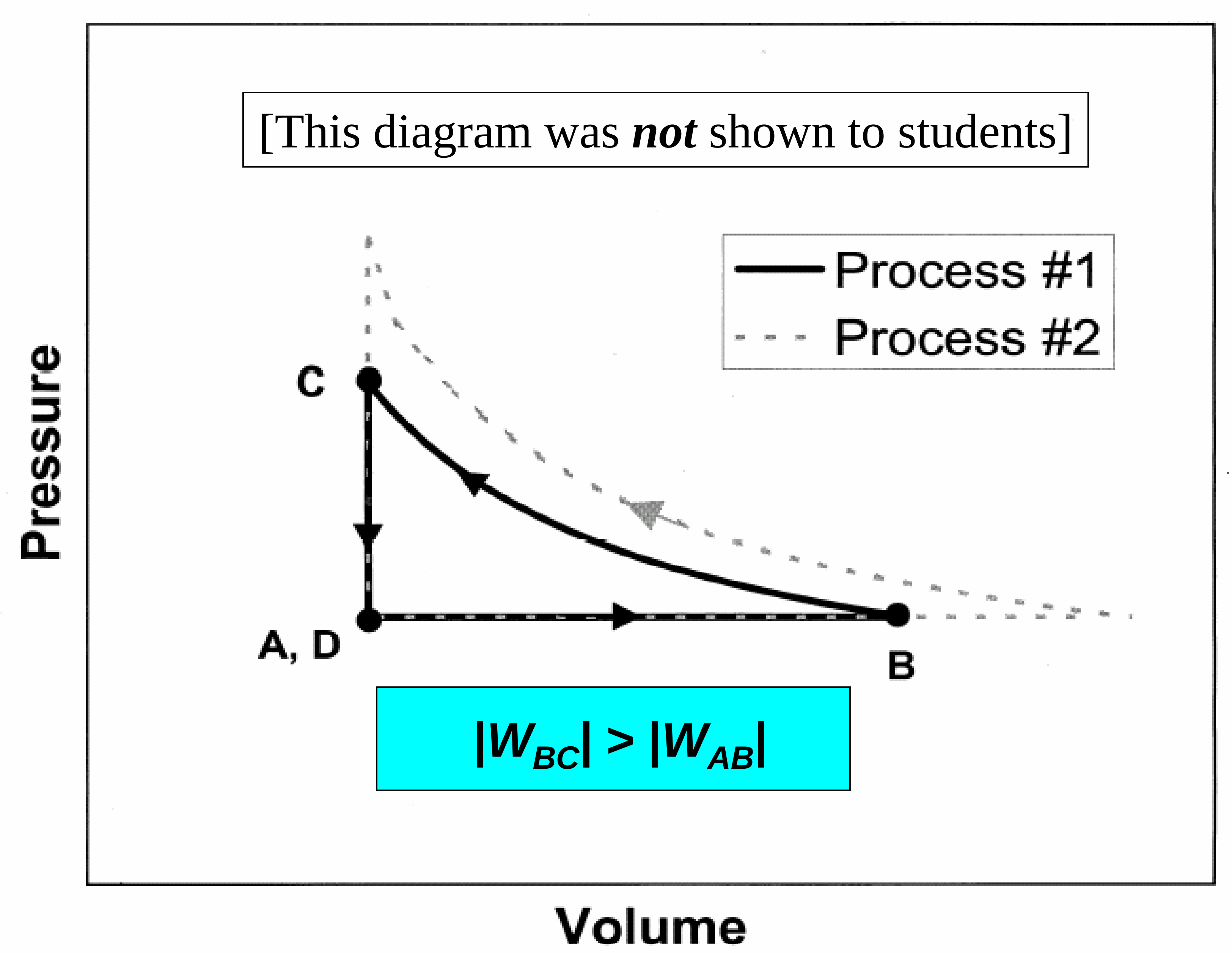
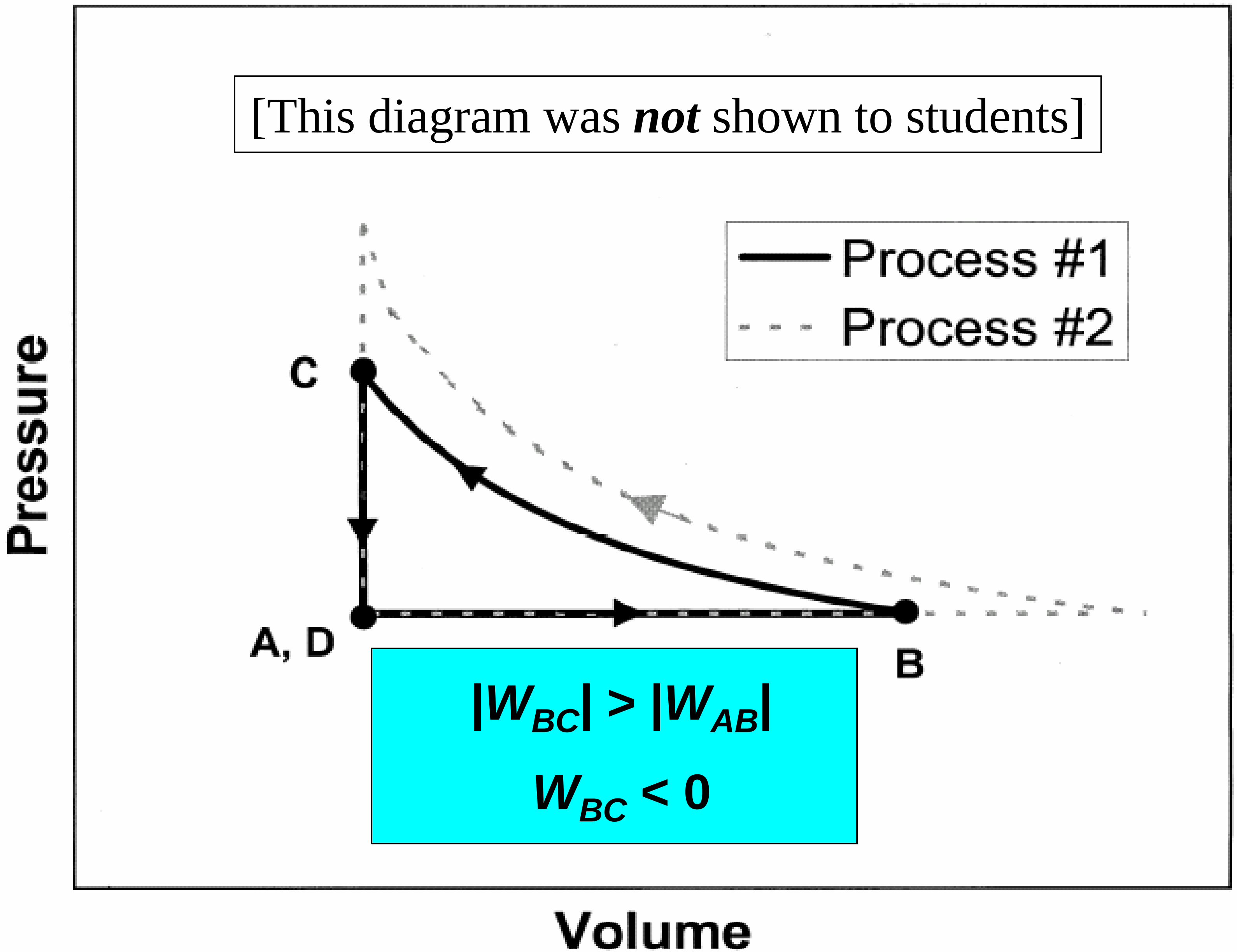
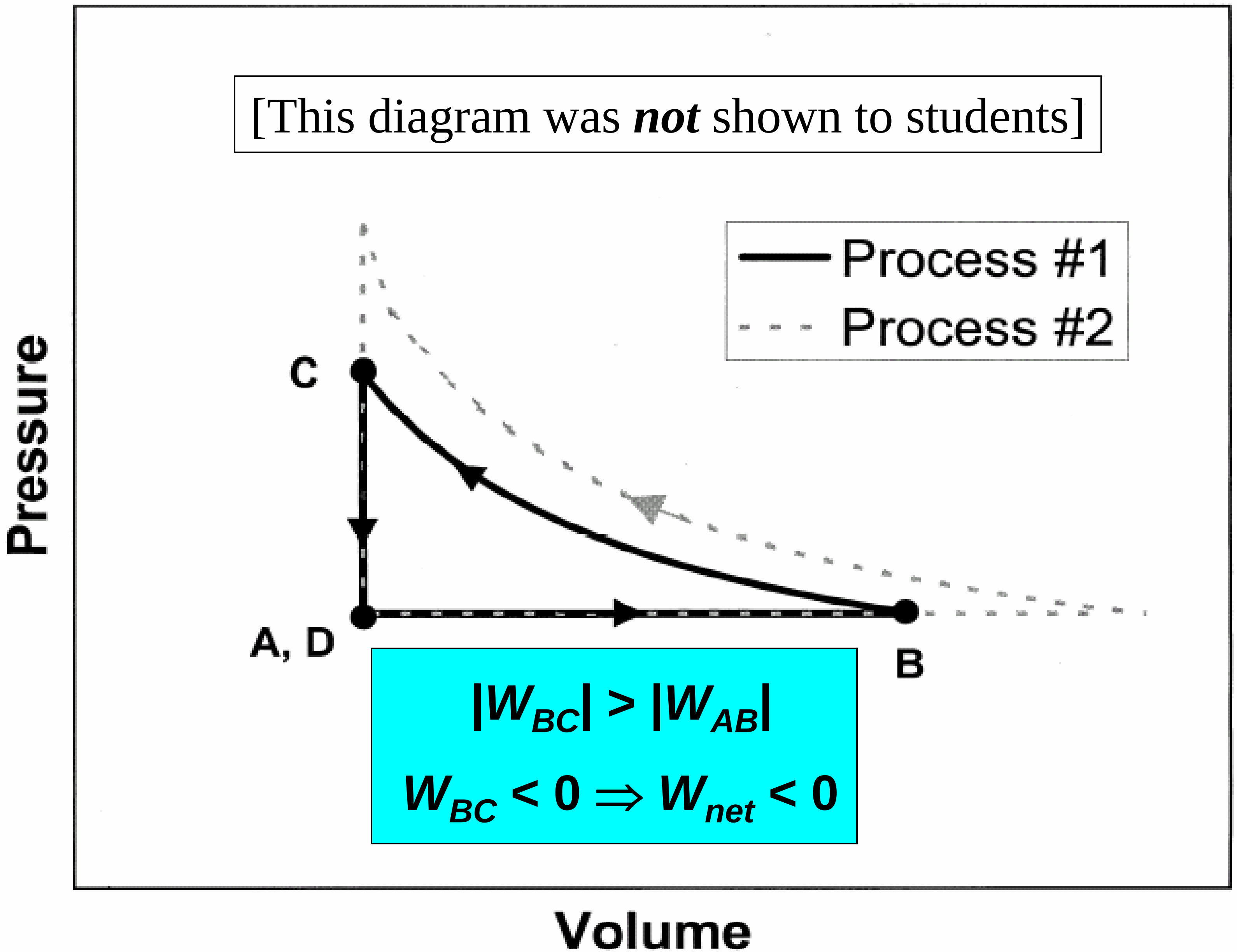
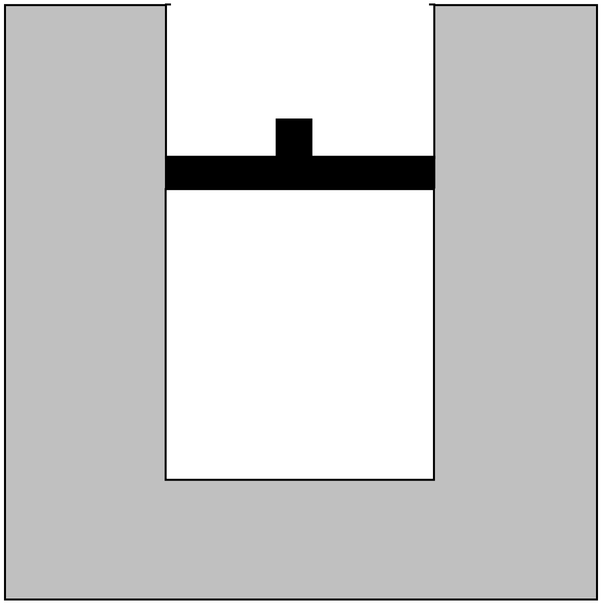
Process #1
Process #2
C
A, D
B
Pressure
Volume



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


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


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



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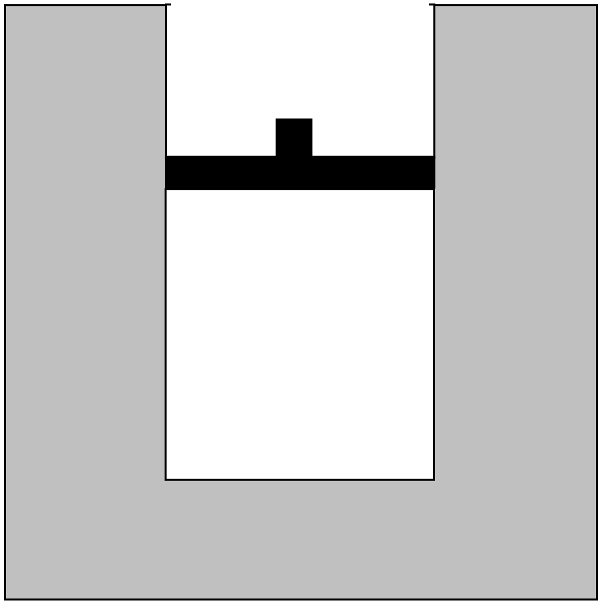

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Results on Question #6 (i)

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

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

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

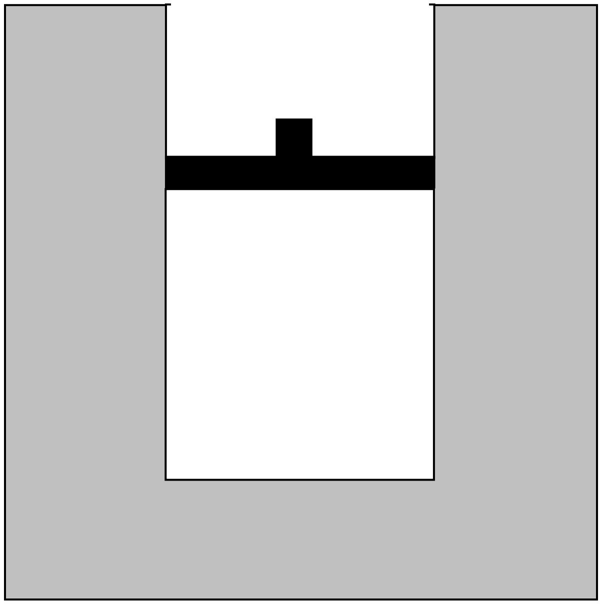
(b) $W_{net} = 0$:

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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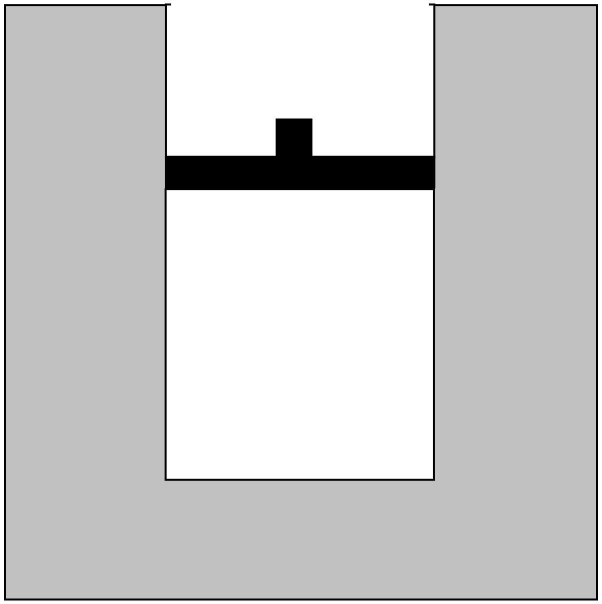

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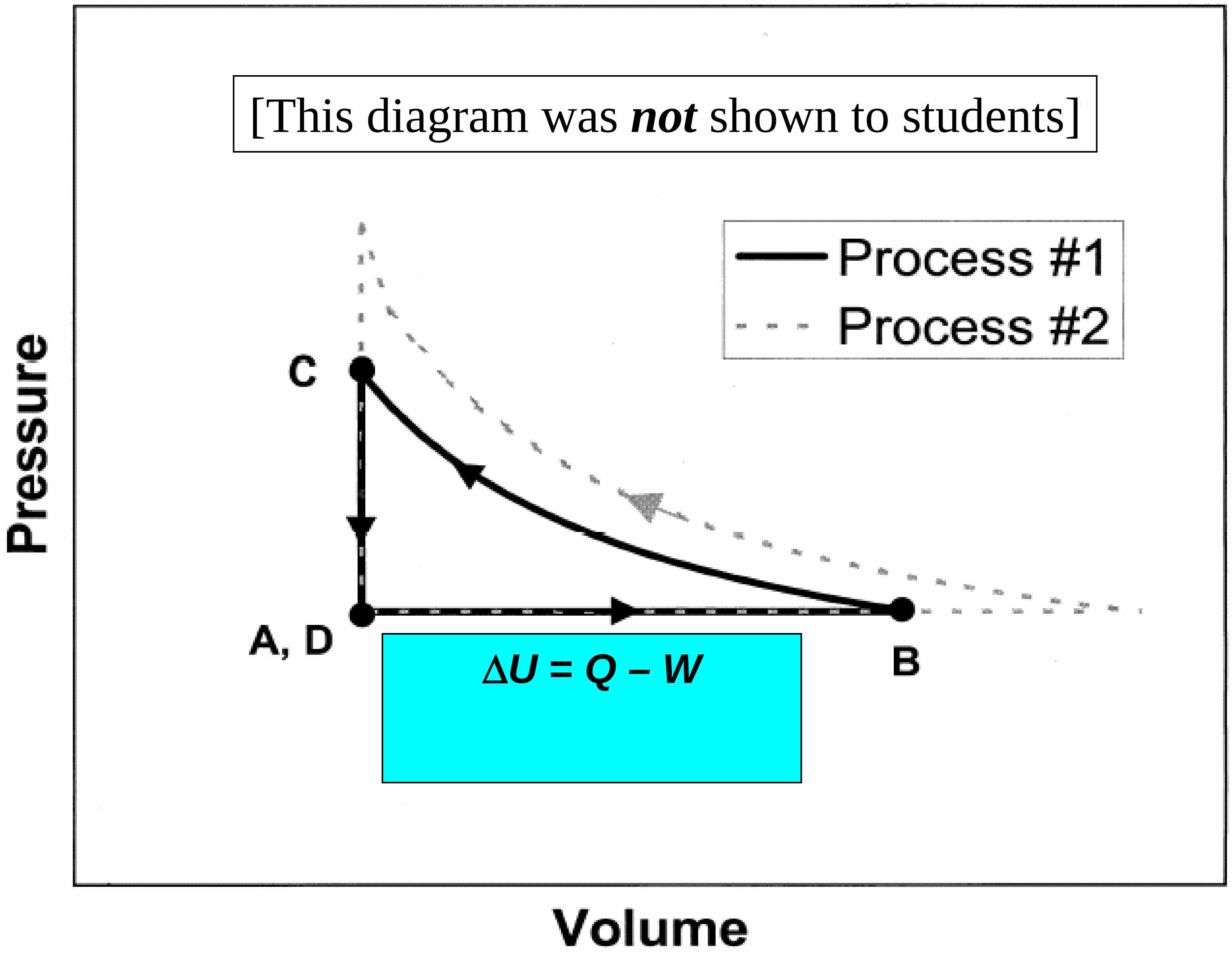
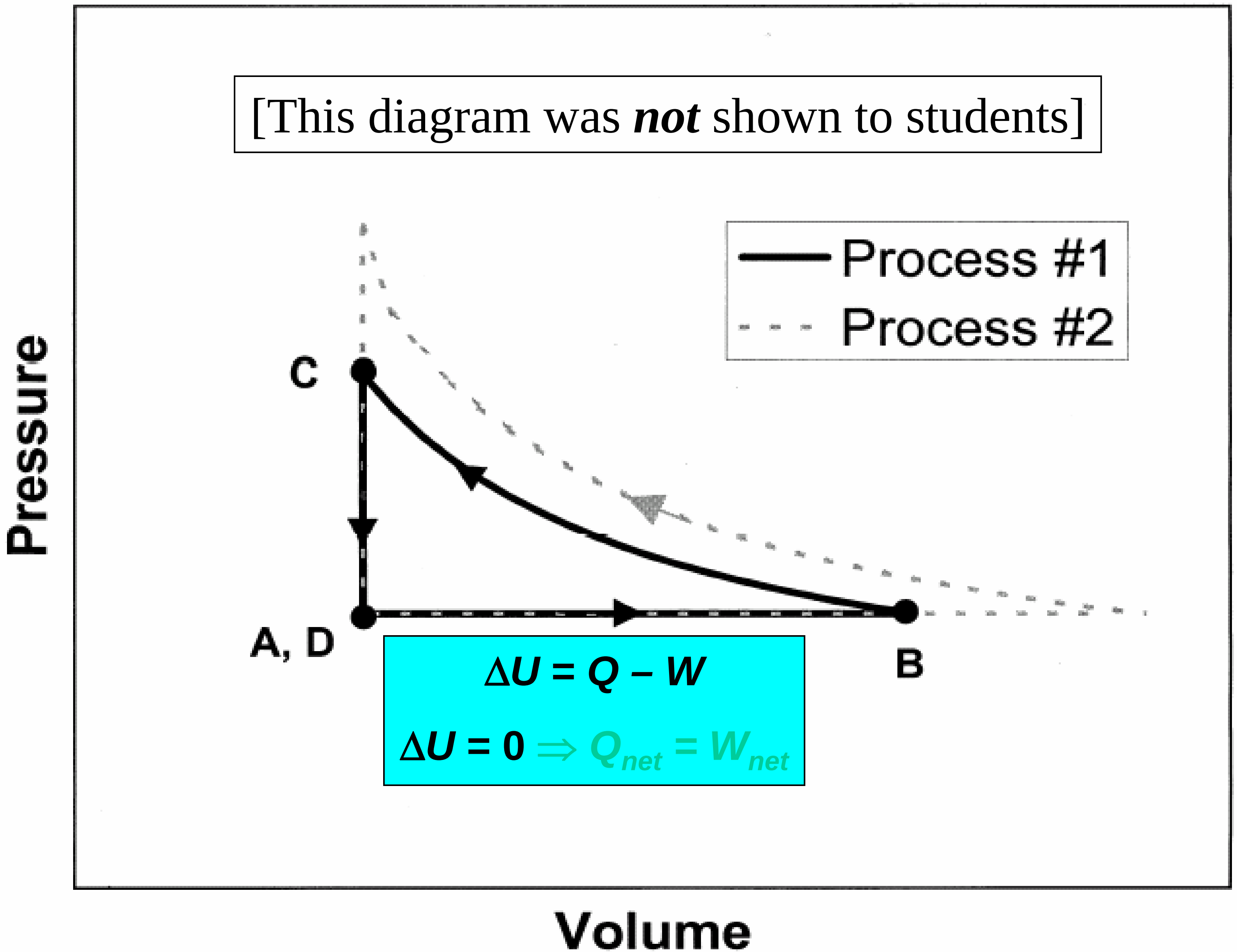
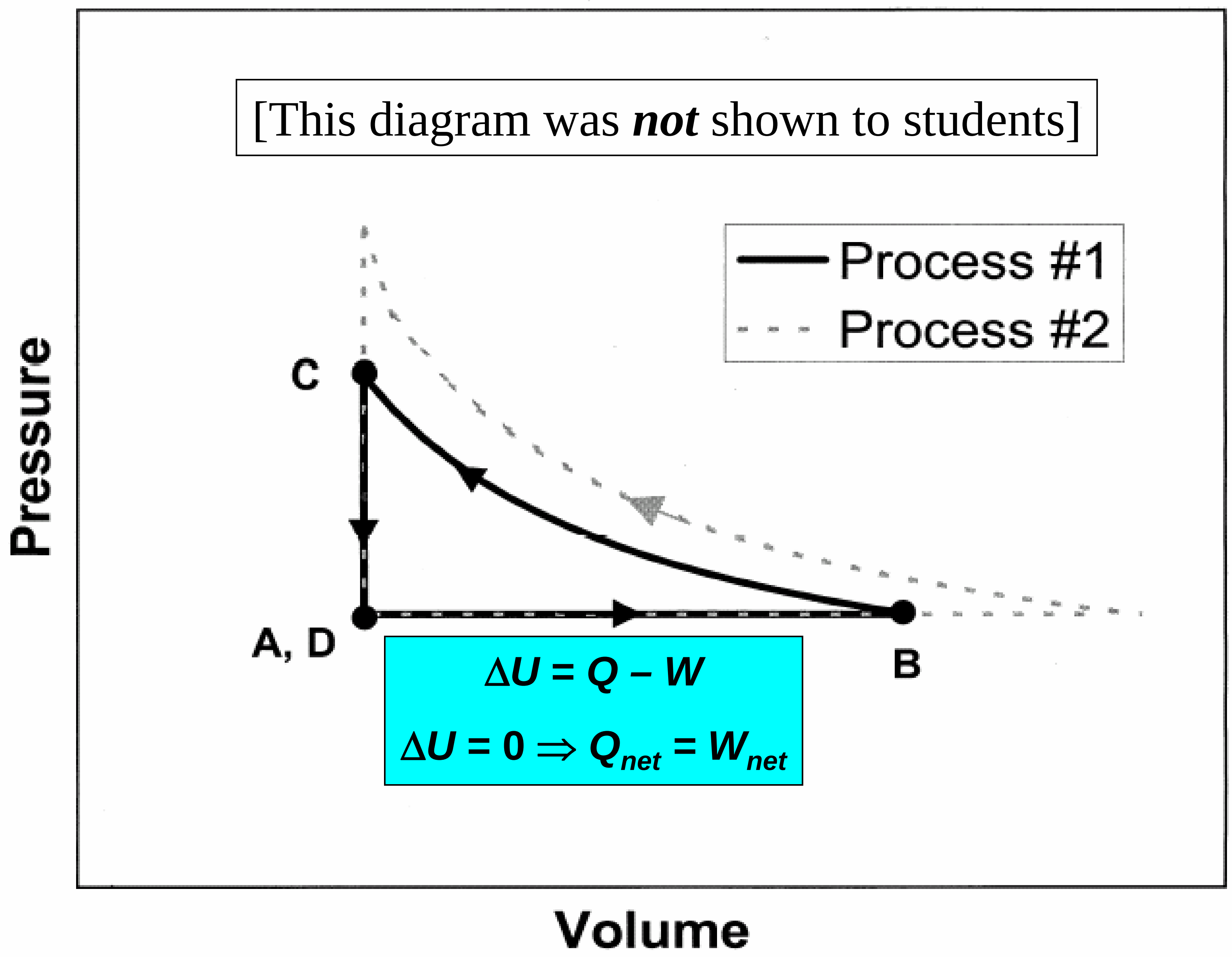
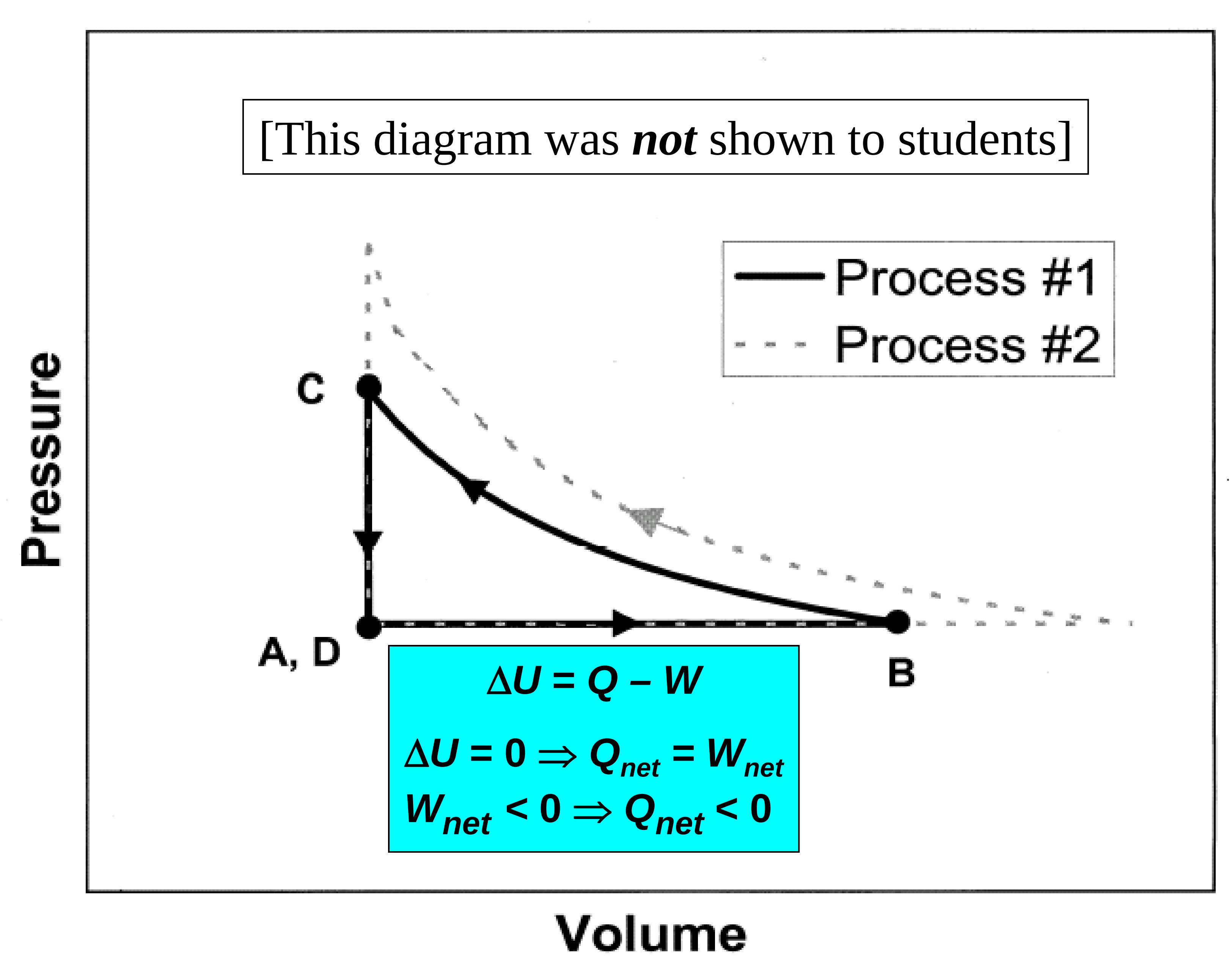
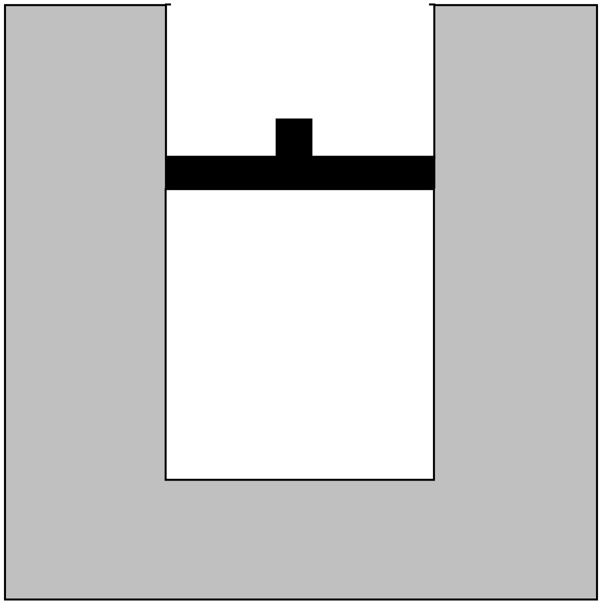

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
ΔU = Q – W
Pressure
Volume


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


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


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



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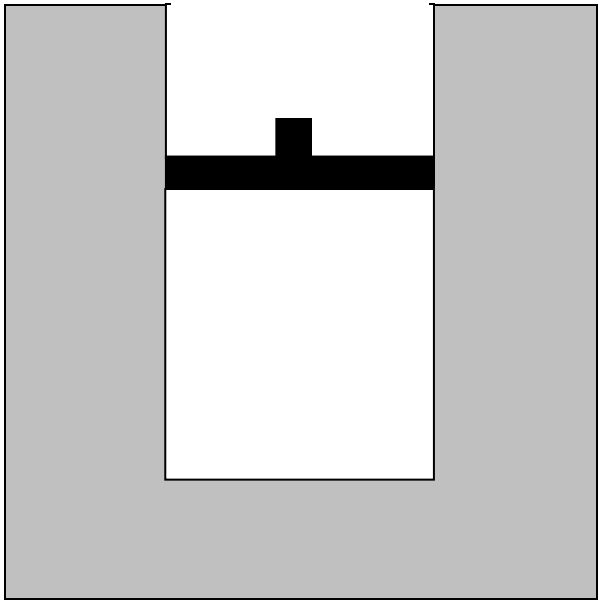

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Results on Question #6 (ii)

(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 $Q_{net} = 0$

"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

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."

Reflects confusion of heat with temperature

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.

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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  - free energy

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

Thermodynamics Curricular Materials

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

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.

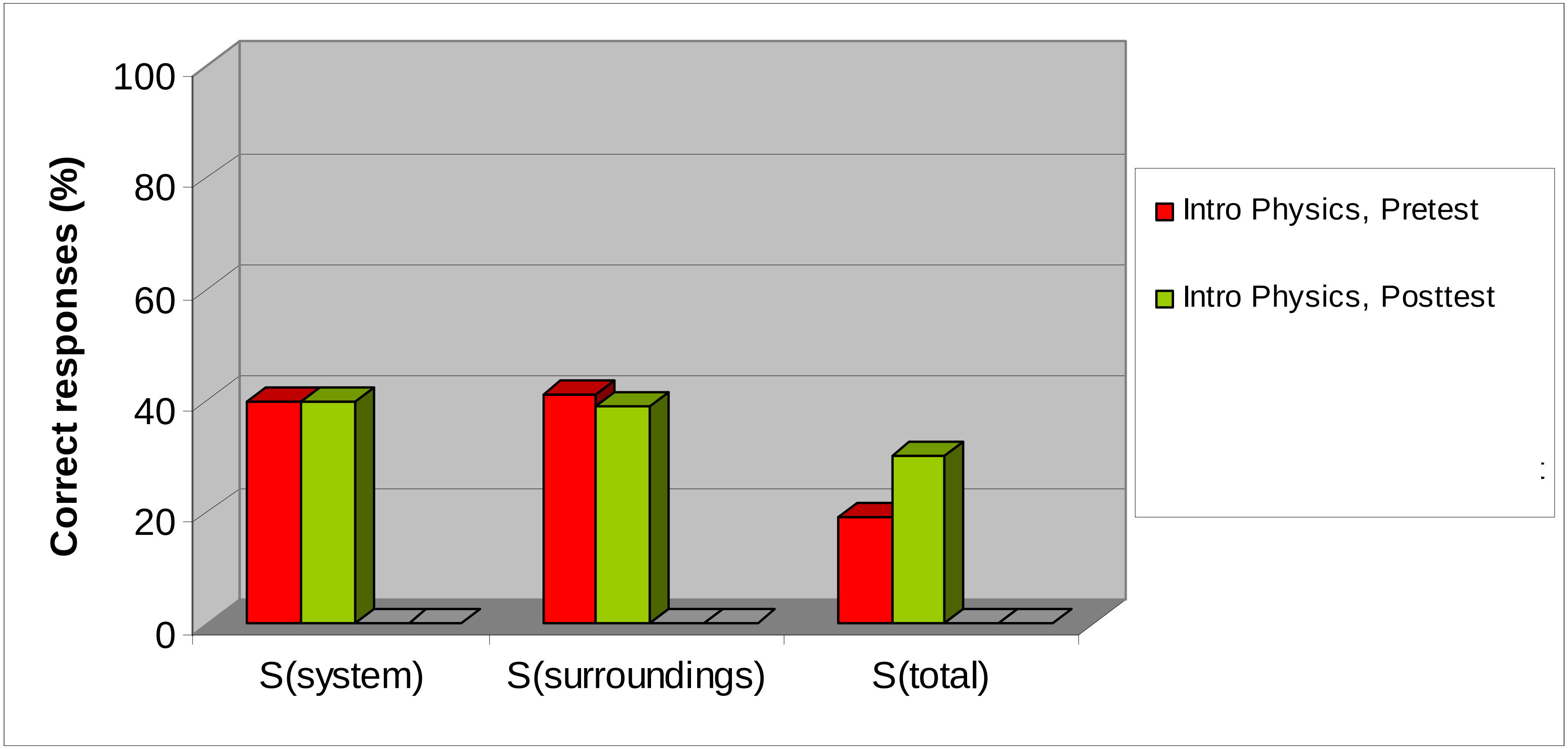
A. During this process, does the entropy of the **system** [S_{system}] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

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.***

Responses to Spontaneous-Process Questions

Introductory Students



Less than 40% correct on each question

Introductory Physics Students' Thinking on Spontaneous Processes

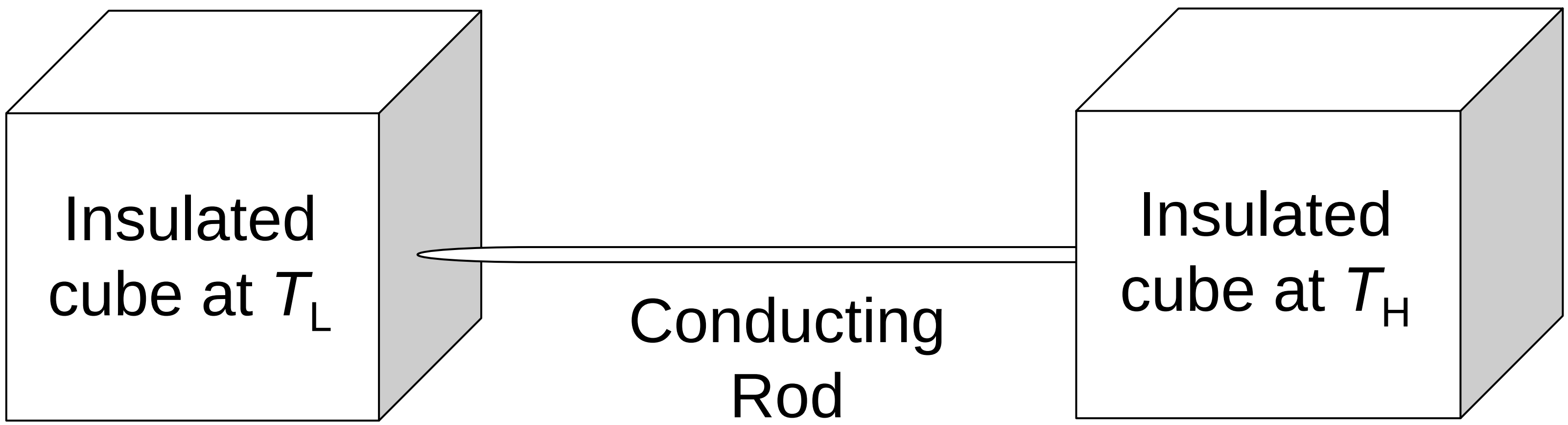
- Tendency to assume that "system entropy" must *always* increase

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

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

Entropy Tutorial

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



• Consider slow heat transfer process between two thermal reservoirs (insulated metal cubes connected by thin metal pipe)

- Does total energy change during process? *[No]*
- Does total entropy change during process? *[Yes]*

Entropy Tutorial

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

- Guide students to find that:

$$\Delta S_{total} = \frac{Q}{T_{cold\ \ reservoir}} - \frac{Q}{T_{hot\ \ reservoir}} > 0$$

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

Preliminary results are promising…

Entropy Tutorial

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

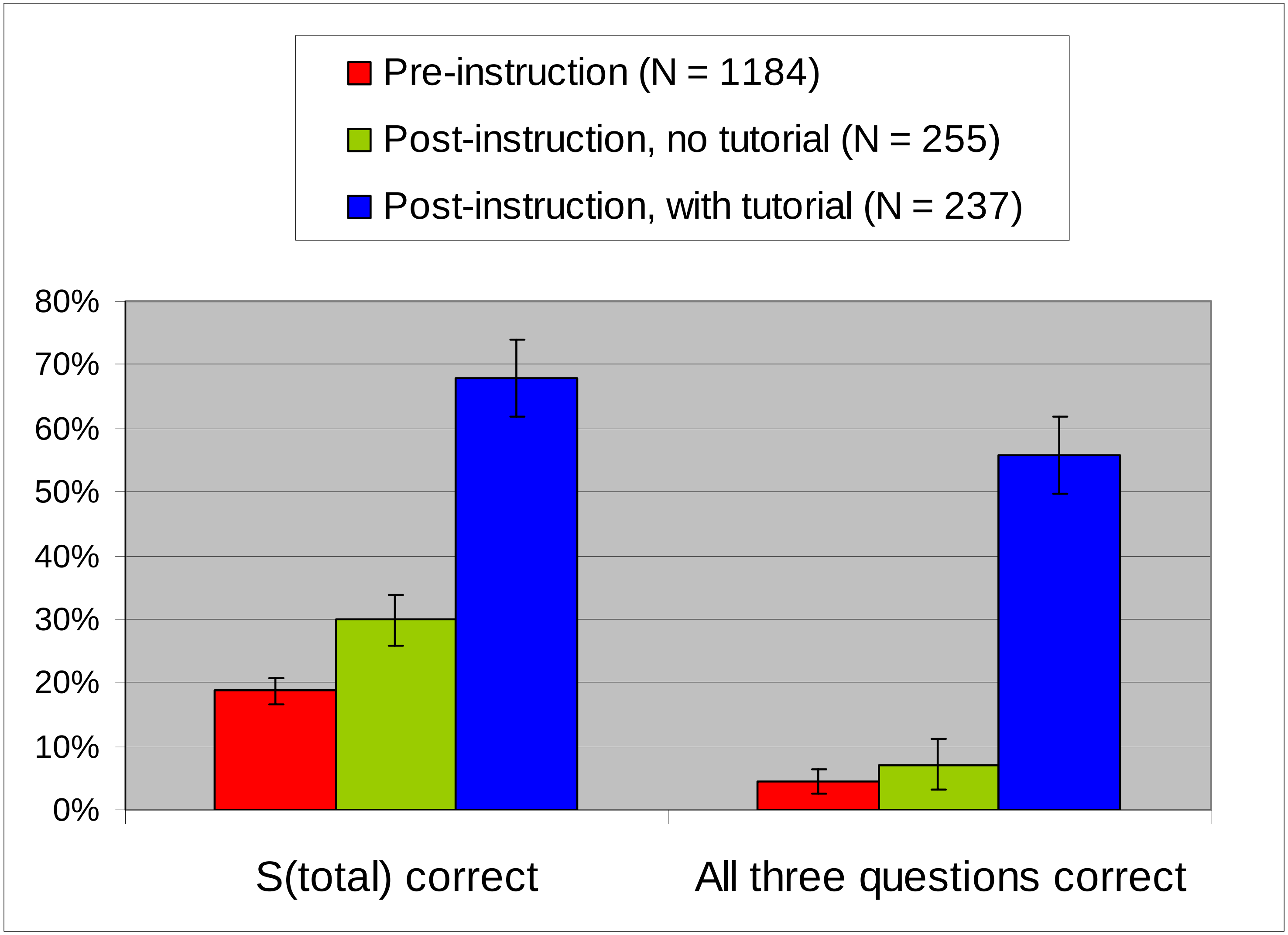
- Guide students to find that:

Entropy gain of low-temperature cube is *larger* than entropy loss of high-temperature cube, so *total entropy increases*

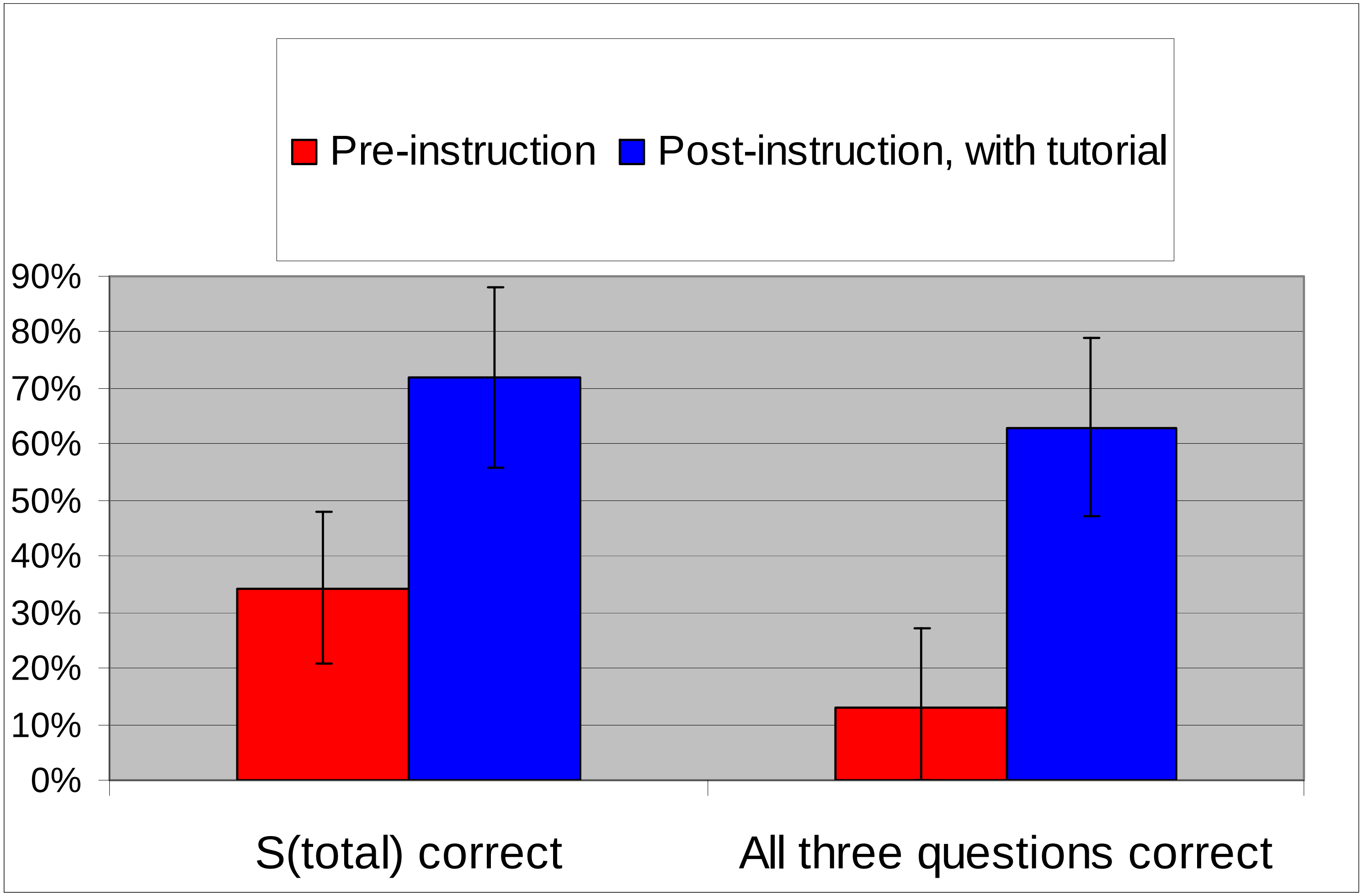
and that definitions of “system” and “surroundings” are arbitrary

Preliminary results are promising…

Responses to Spontaneous-Process Questions
Introductory Students



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



Summary

- Research on student learning lays basis for development of improved instructional materials in science education.
- “Interactive-engagement” instruction using research-based curricula can improve student learning.
- Treating science education as a research problem holds promise of cumulative progress, based on solid foundation of previous results.

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