Investigating and Improving Student Learning through Physics Education Research

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

Outline

- Overview of goals and methods of PER

Investigation of Students’ Reasoning:

- Students’ reasoning in thermodynamics
- Diverse representational modes in student learning

Curriculum Development:

- Instructional methods and curricular materials for large-enrollment physics classes

Assessment of Instruction:

- Measurement of learning gain
- Potential broader impact of PER on undergraduate education

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Goals of PER

- Improve effectiveness and efficiency of physics instruction
  - measure and assess *learning* of physics (not merely *achievement*)
- 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
  - focus on maximizing achievement of best-prepared students?
  - achieve significant learning gains for majority of enrolled students?

- Specify the goals of instruction in particular learning environments
  - physics concept knowledge
  - quantitative problem-solving ability

Time Burden of Empirical Research

- Many variables (student demographics, instructor style, course logistics, etc.)
  - hard to identify
  - difficult to estimate relative importance
  - difficult (or impossible) to control

⇒ Fluctuations from one data run to next tend to be large

  - increases importance of replication

- Each data run requires entire semester

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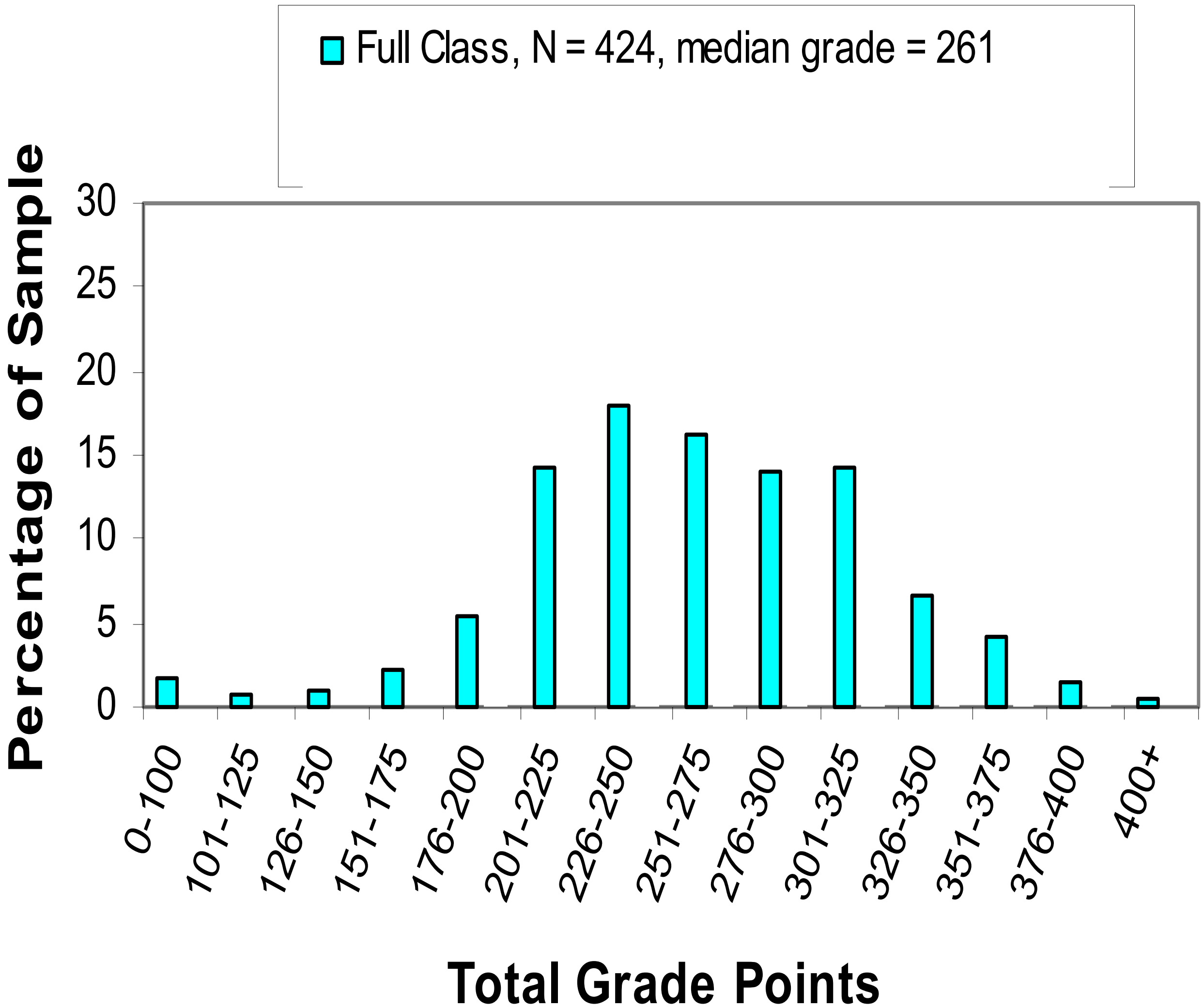
Research Basis for Curriculum Development *(NSF CCLI Project with T. Greenbowe)*

- 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*

[two course instructors, ≈ 20 recitation instructors]

Grade Distributions: Interview Sample vs. Full Class



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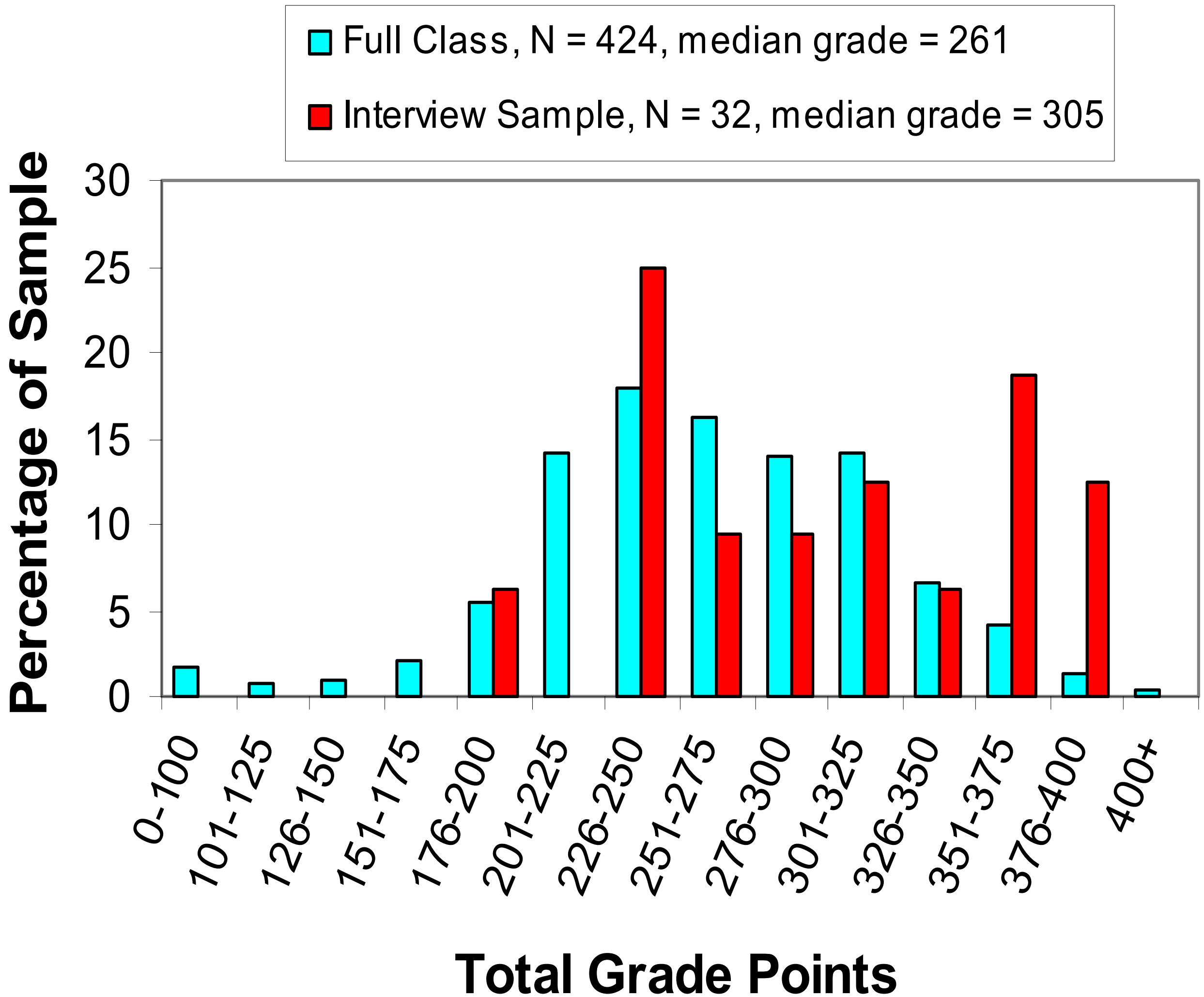

***Interview Sample*:**

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 absorbed by a system undergoing a cyclic process are zero.
5. Inability to apply the first law of thermodynamics.

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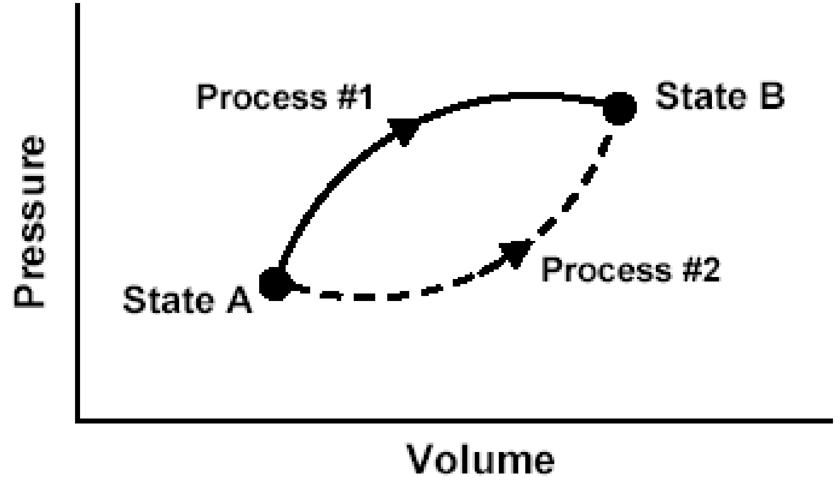
Understanding of Concept of State Function in the Context of Energy

- 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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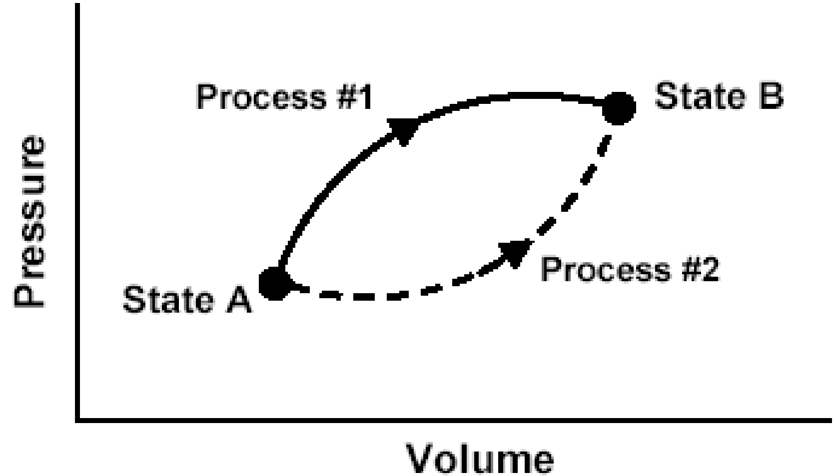

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Students seem to have adequate grasp of state-function concept

- Consistently high percentage (70-90%) of correct responses on relevant questions.
- Large proportion of correct 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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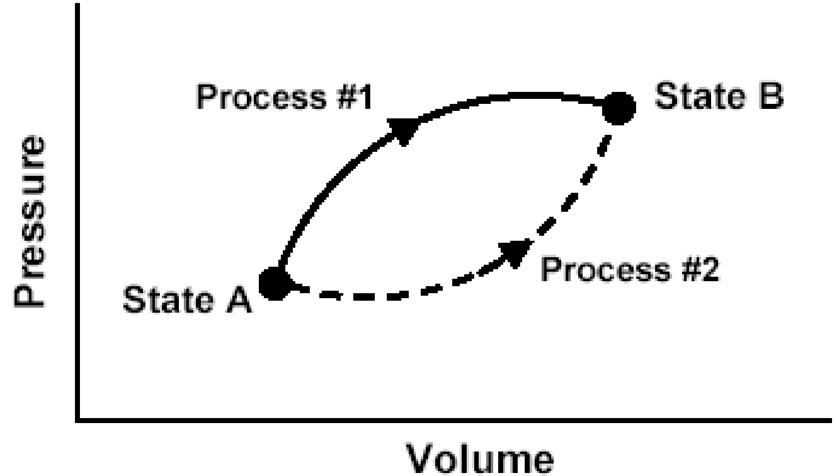

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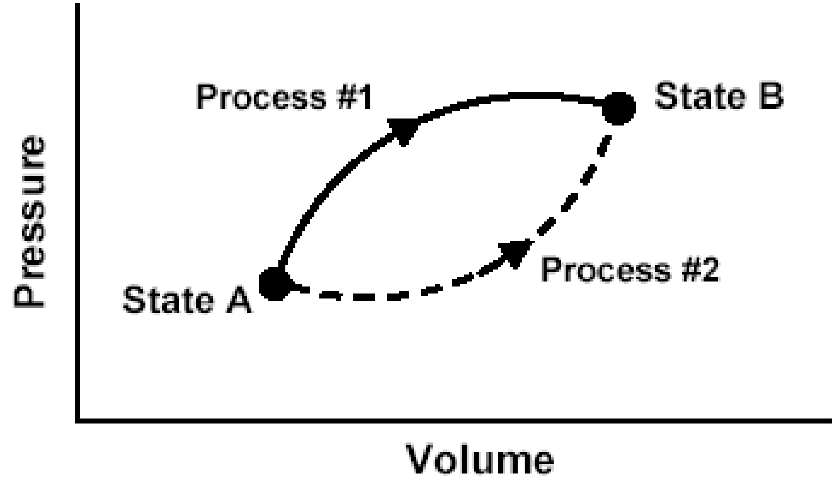
$$W = \int_{V_A}^{V_B} P\,dV$$



$$W_1 > W_2$$

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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)
$W_1 = W_2$	**25%**	**26%**	**35%**	**22%**
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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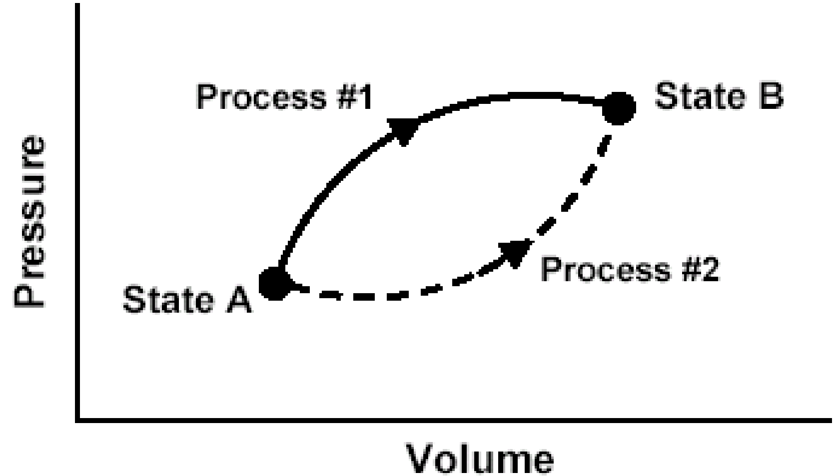

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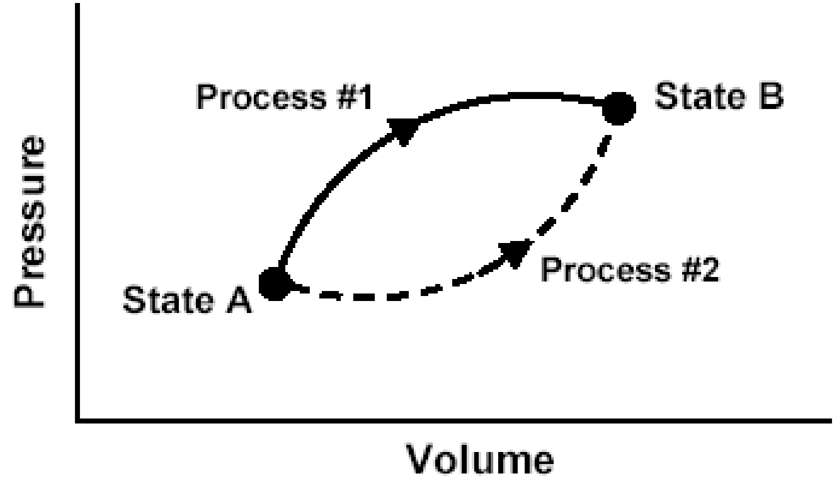
Change in internal energy is the same for Process #1 and Process #2.



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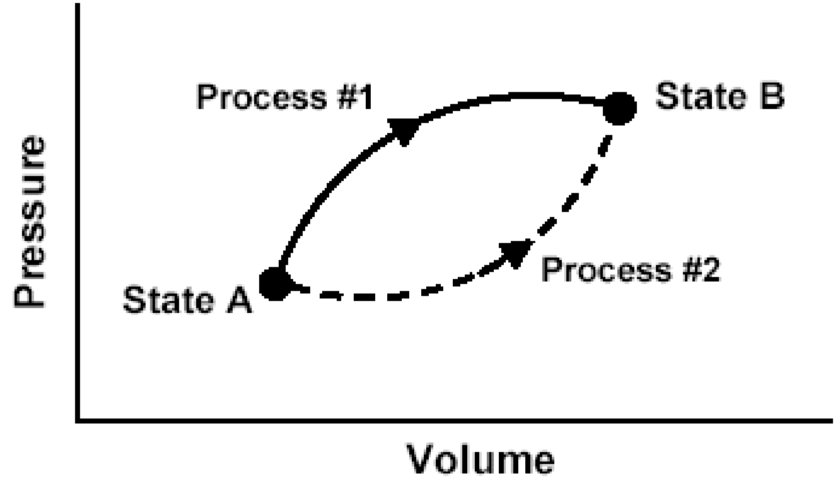
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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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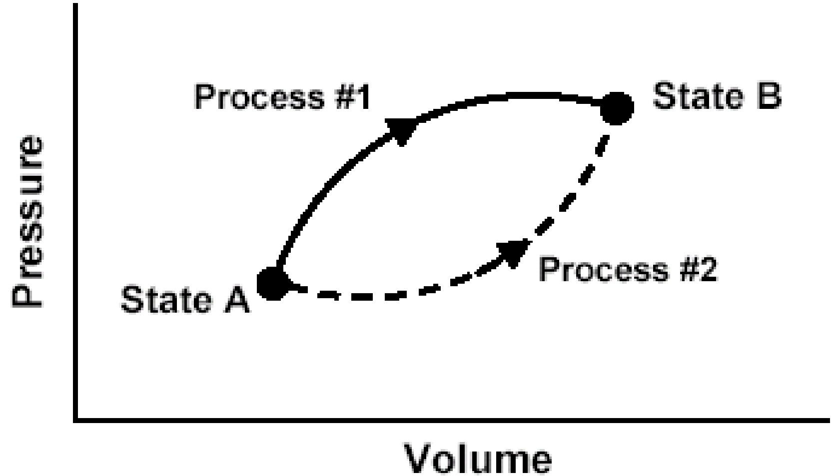
Algebraic Method:

$$\Delta U_1 = \Delta U_2$$

$$Q_1 - W_1 = Q_2 - W_2$$

$$W_1 - W_2 = Q_1 - Q_2$$

$$W_1 > W_2 \Rightarrow Q_1 > Q_2$$



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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)
$Q_1 = Q_2$	**31%**	**43%**	**41%**	**47%**
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 200 students offered arguments similar to these either in their written responses or during the interviews.**

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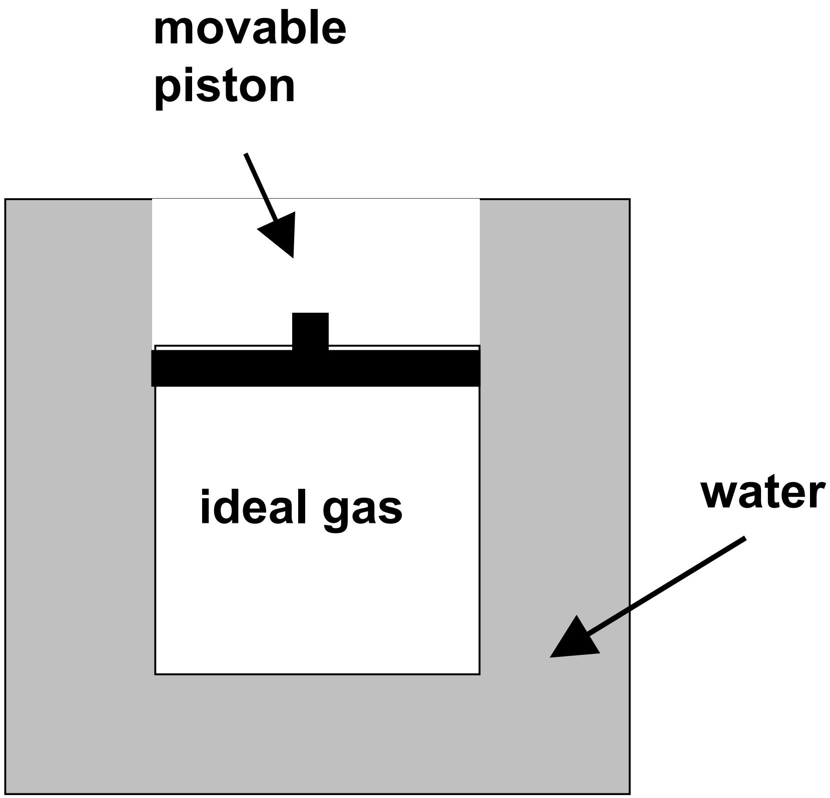
Interview Questions

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

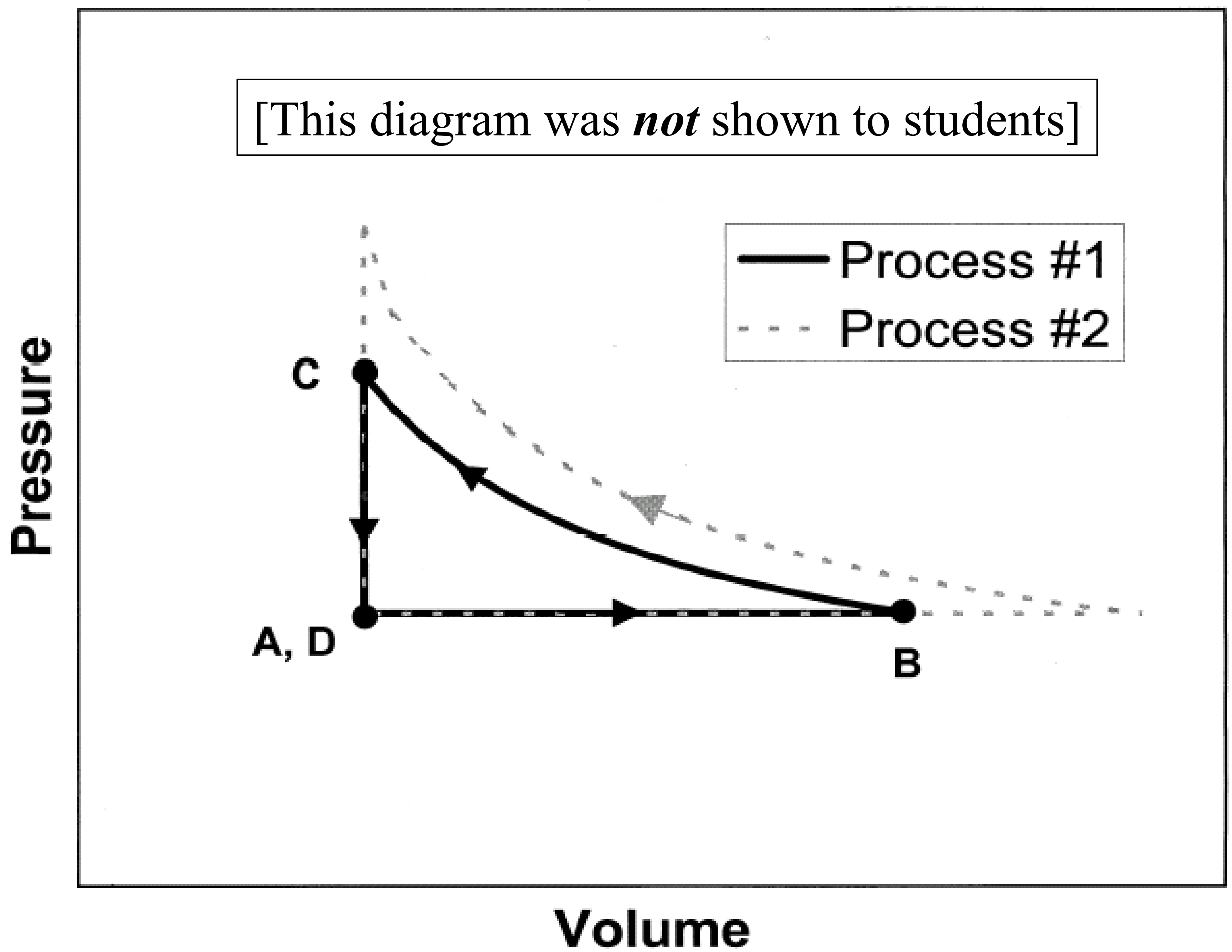
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

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

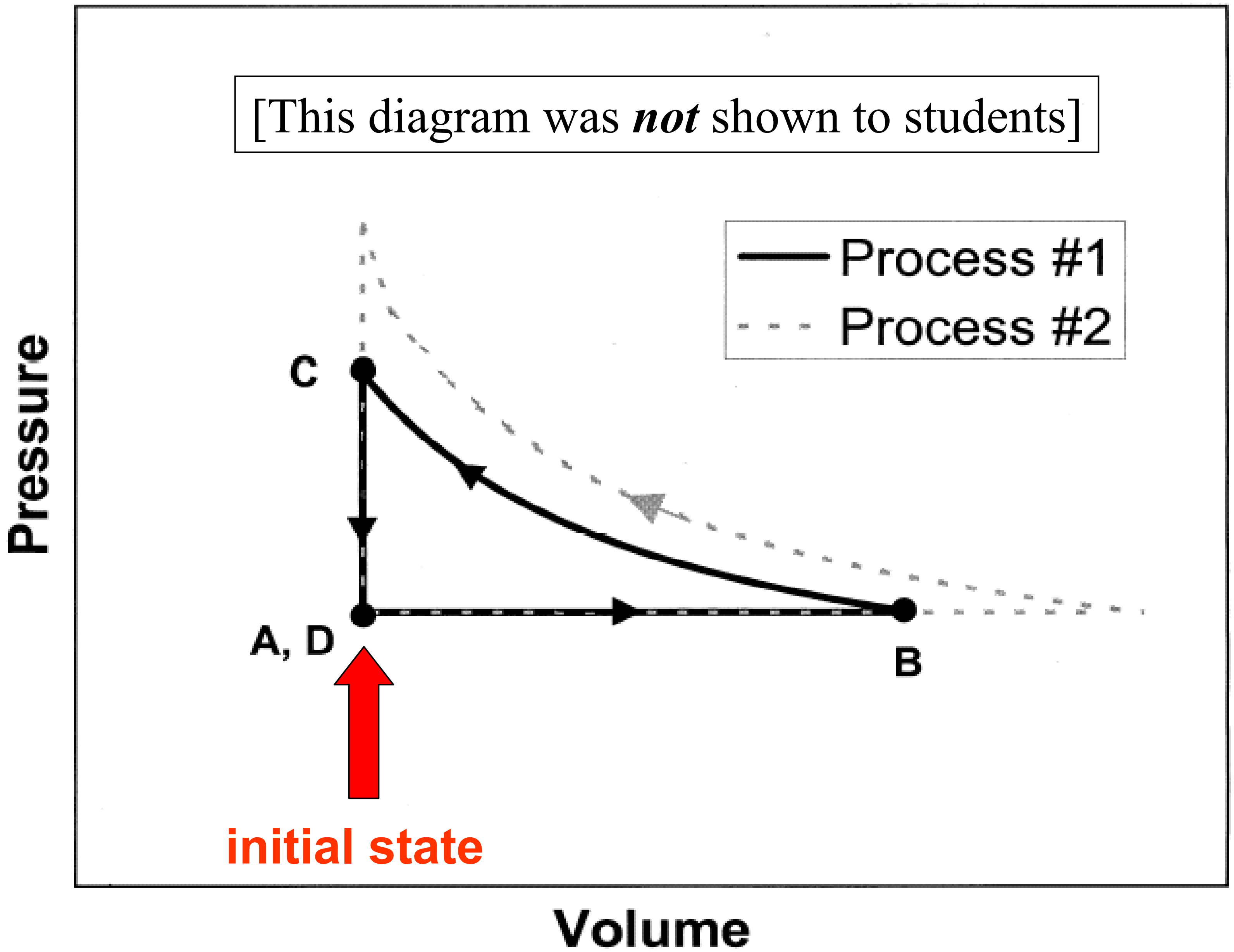


Time *A*

Entire system at room temperature.



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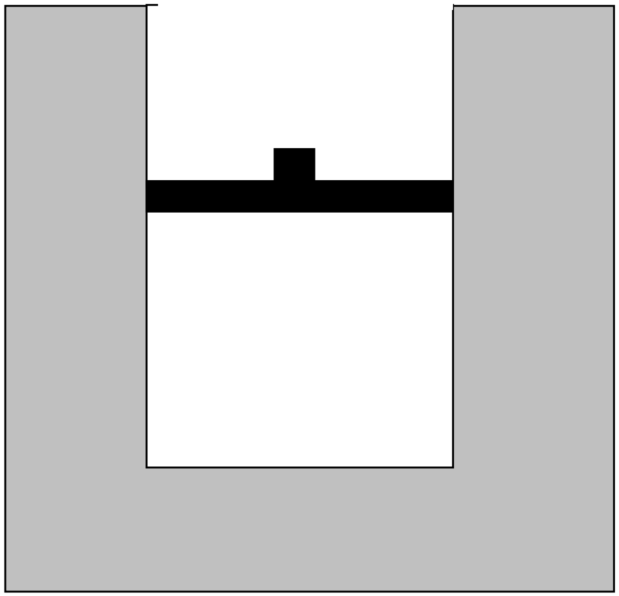
Process #1
Process #2
C
A, D
B
initial state
Pressure
Volume

Step 1. We now begin Process #1: 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 when it is in the position shown in the diagram below:



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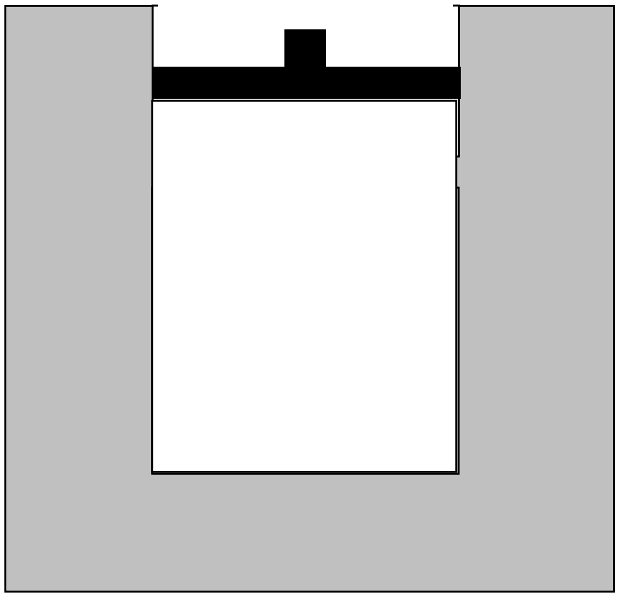
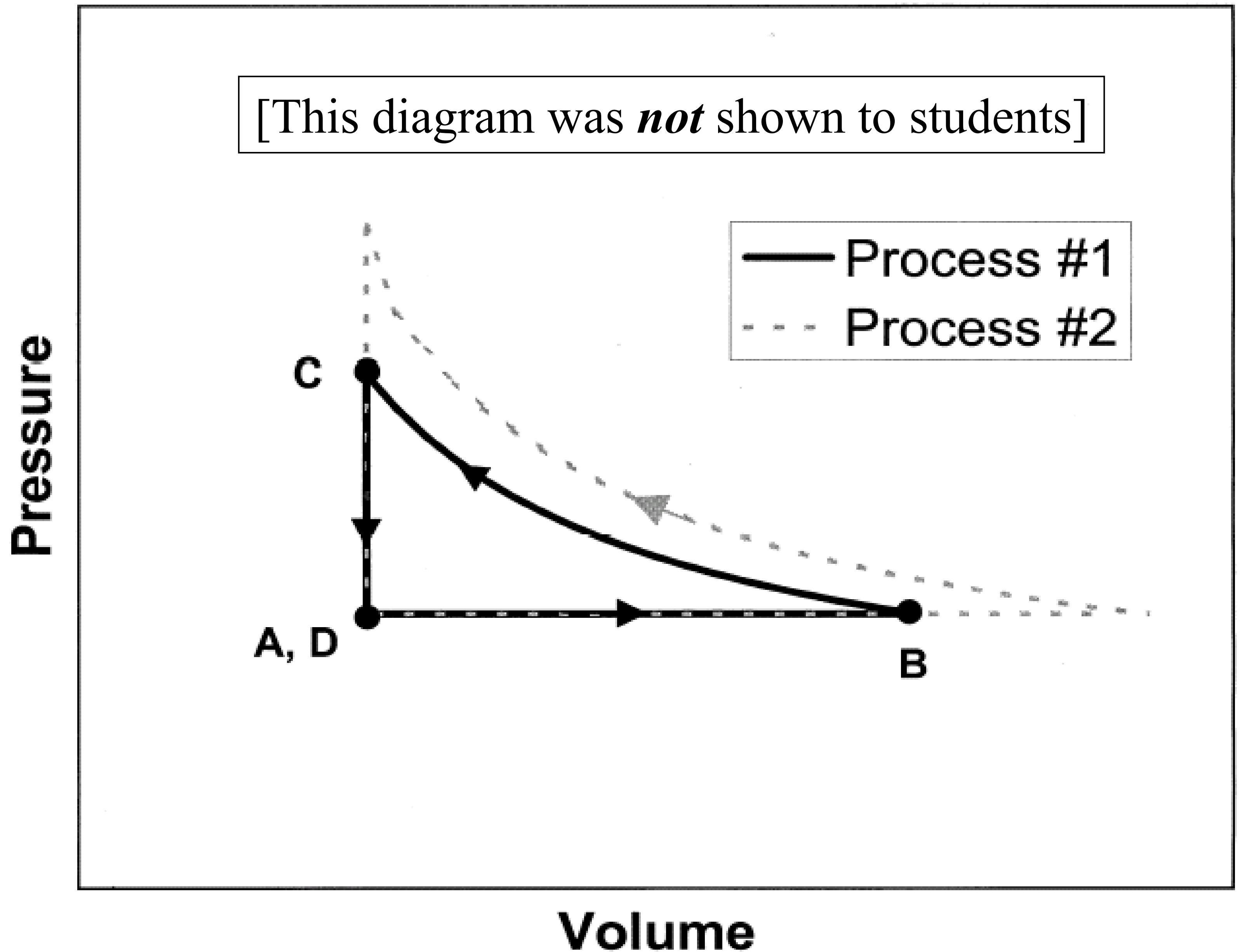
Time *B*

Piston in new position.

Temperature of system has changed.

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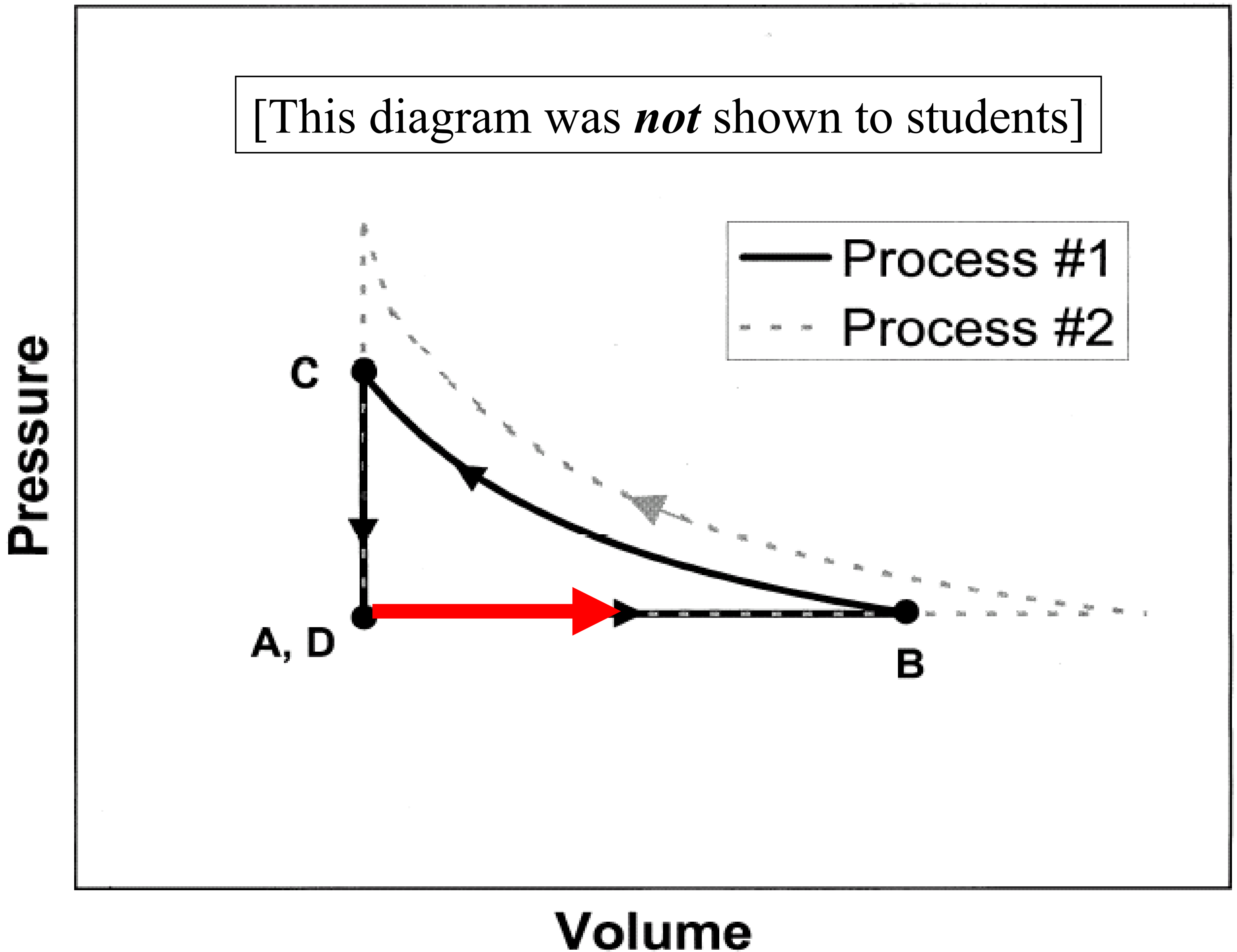
B
Pressure
Volume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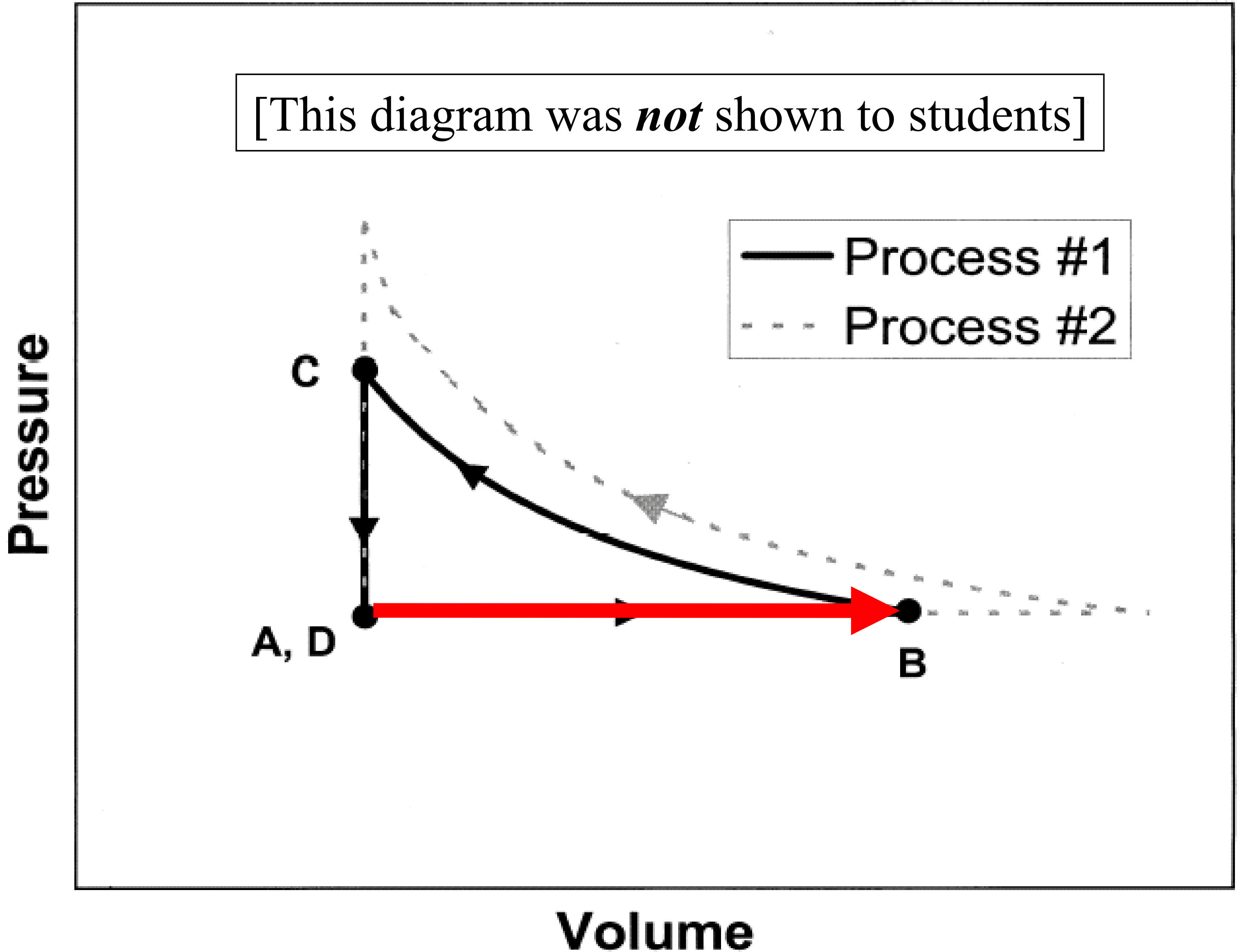
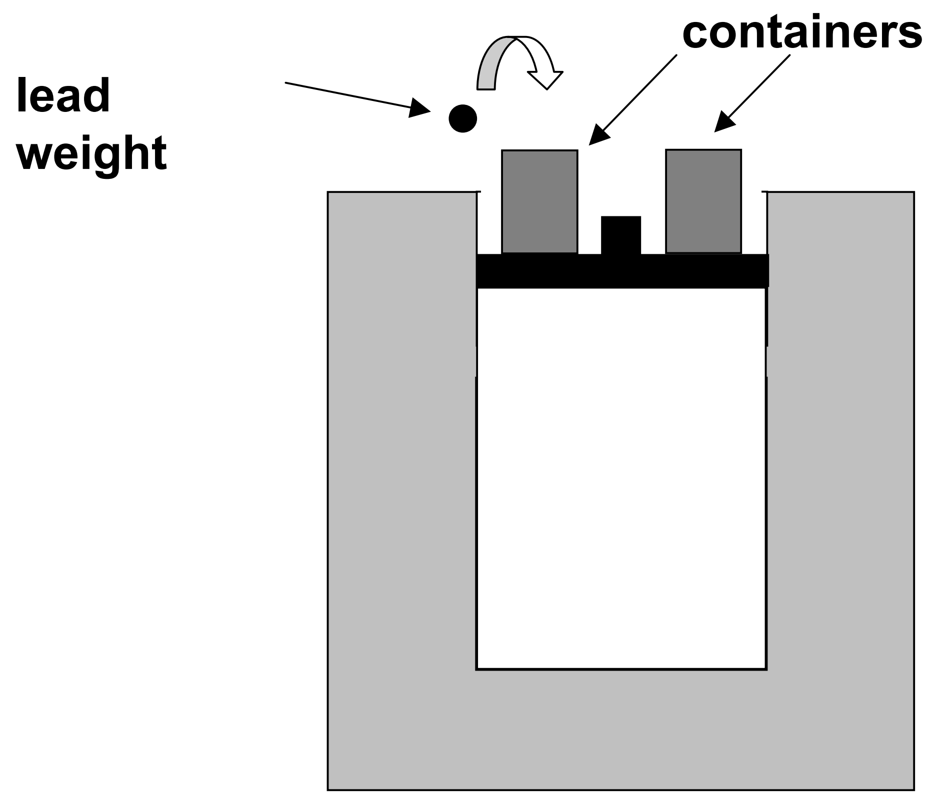


Step 2. Now, empty containers are placed on top of the piston as shown. Small lead weights are gradually placed in the containers, one by one, and the piston is observed to move down slowly. While this happens, the temperature of the water is nearly unchanged, and the gas temperature remains practically *constant*. (That is, it remains at the temperature it reached at time *B,* after the water had been heated up.)



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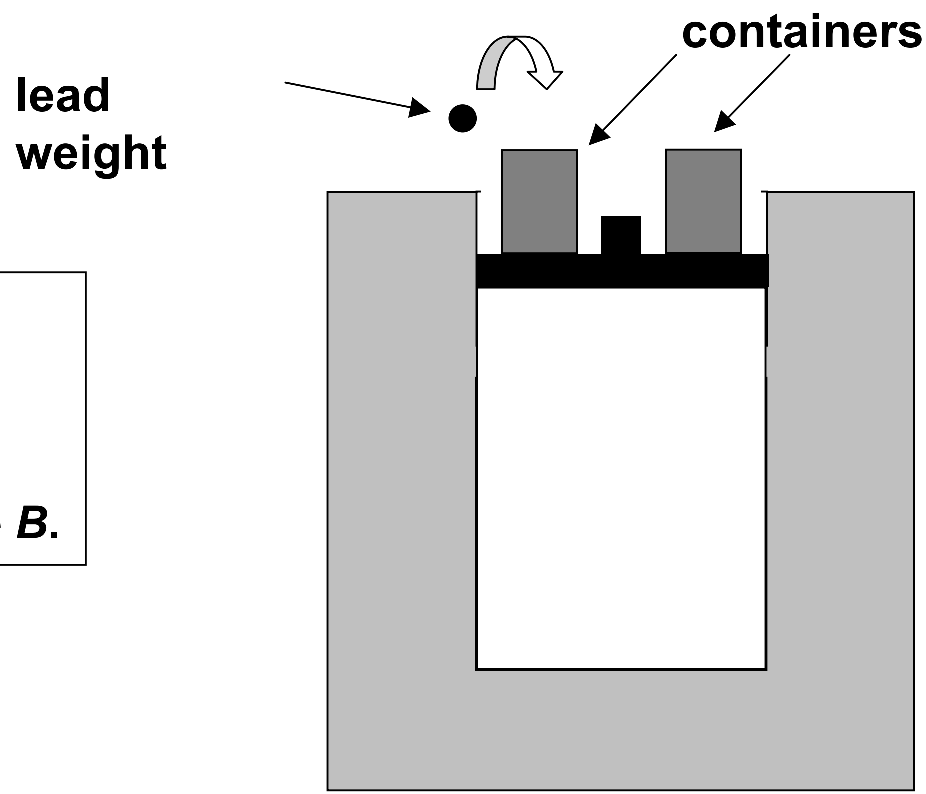
weights being added

Piston moves down slowly.

Temperature remains same as at time *B*.



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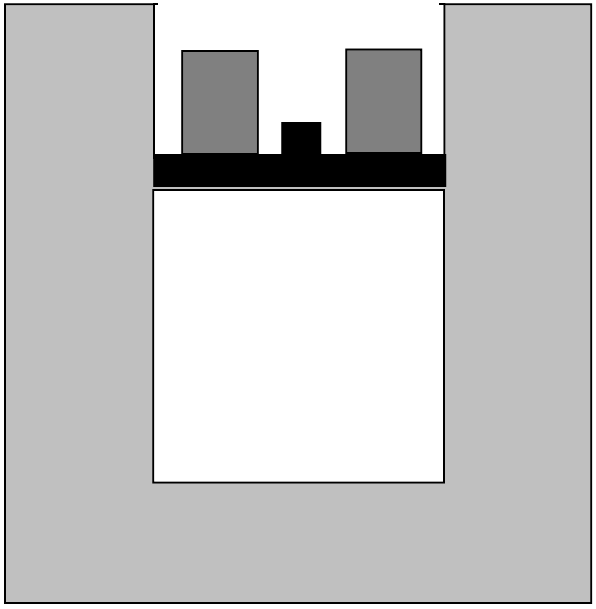
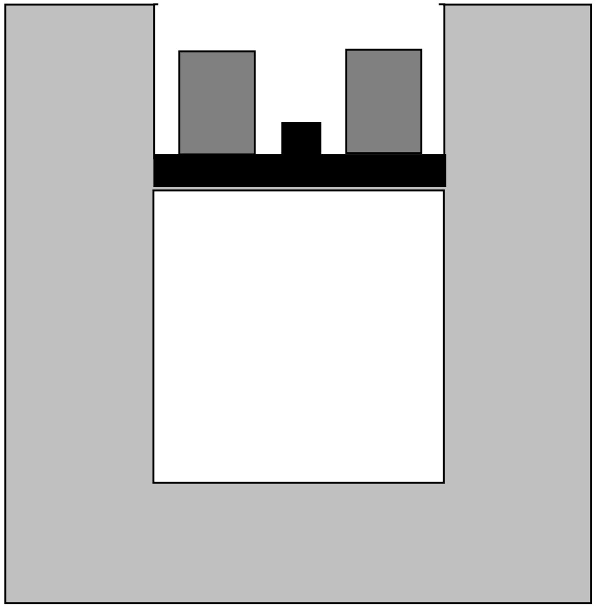


Step 3. At time *C* we stop adding lead weights to the container and the piston stops moving. (The weights that we have already added up until now are still in the containers.) The piston is now found to be at *exactly the same position it was at time* ***A*** .



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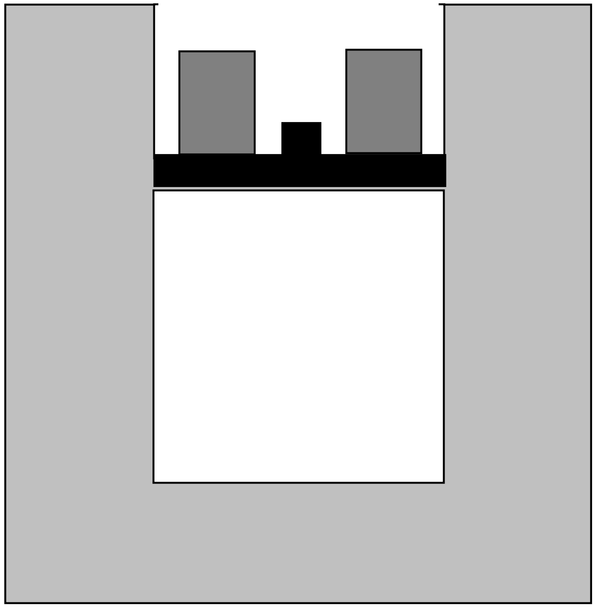
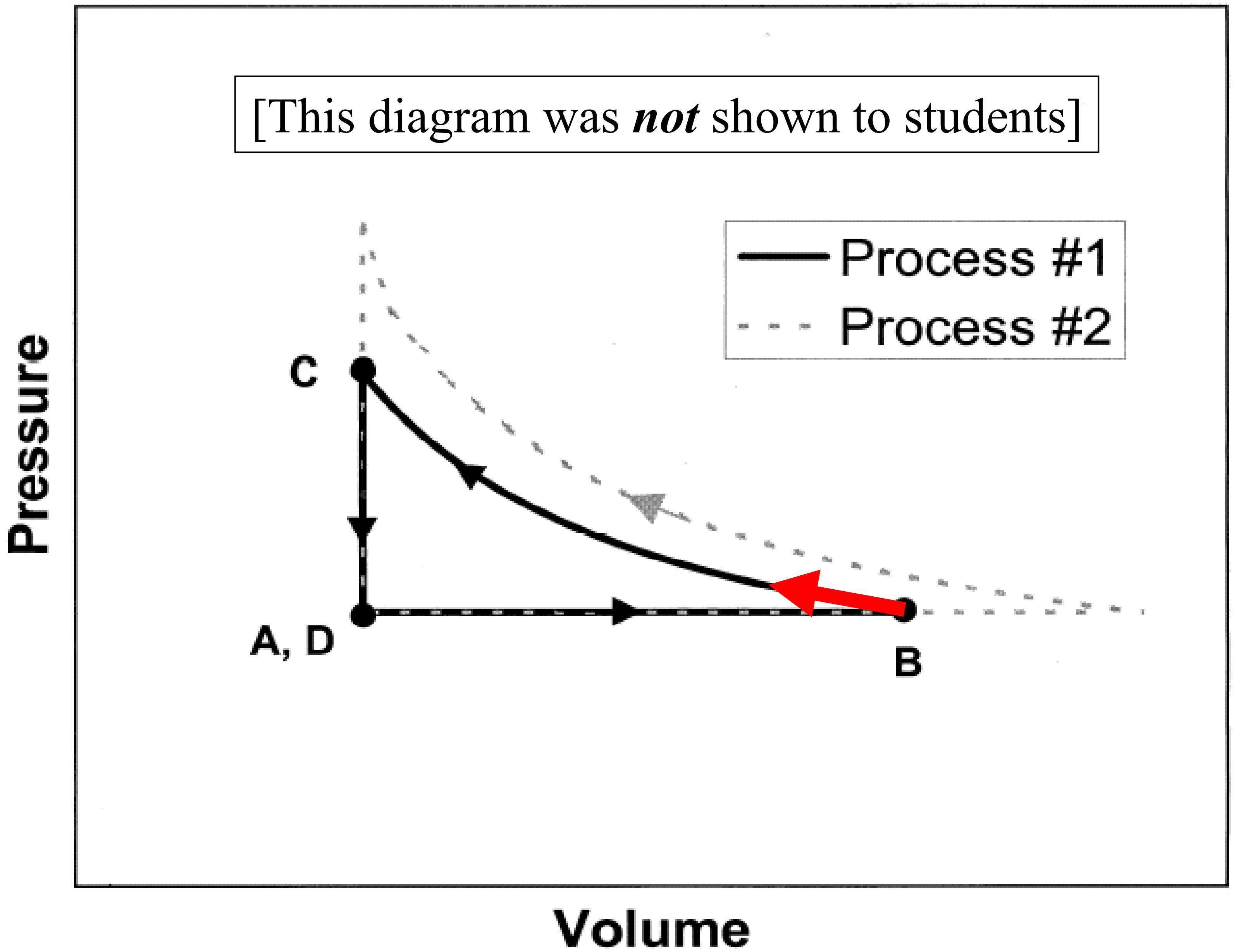
Time *C*

Weights in containers.

Piston in same position as at time *A*.

Temperature same as at time *B*.

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Process #2
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A, D
B
Pressure
Volume

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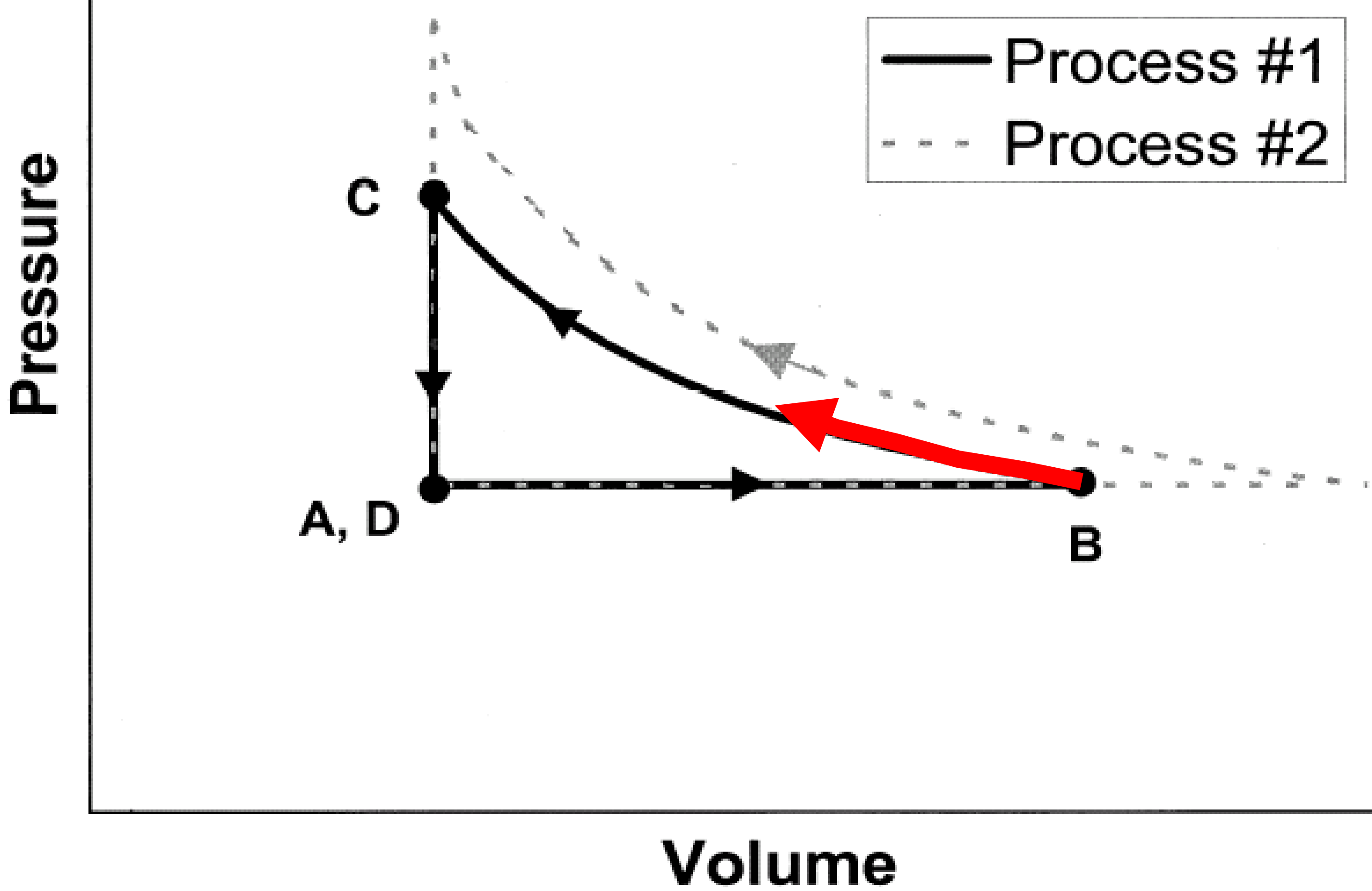

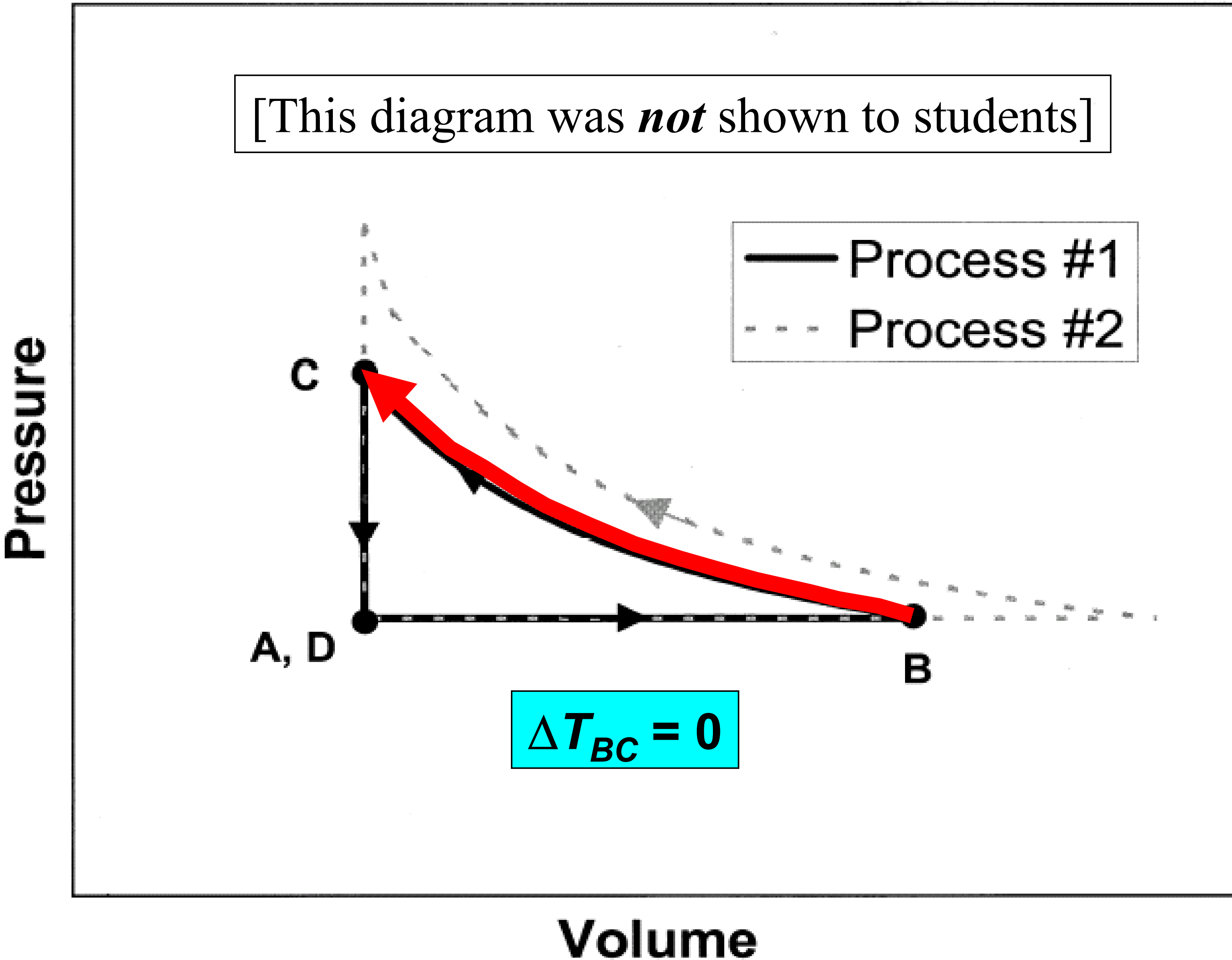
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C
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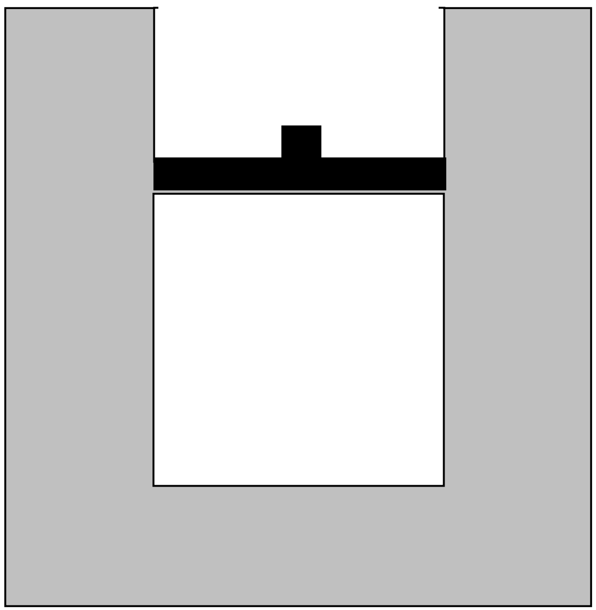
$\Delta T_{BC} = 0$
Pressure
Volume

Step 4. Now, the piston is locked into place so it *cannot move*; the weights are removed from the piston. The system is left to sit in the room for many hours, and eventually the entire system cools back down to the same room temperature it had at time *A.* When this finally happens, it is time *D*.



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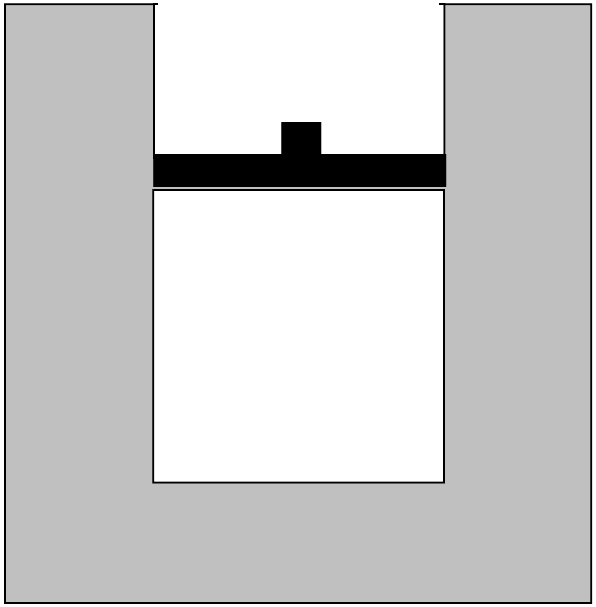
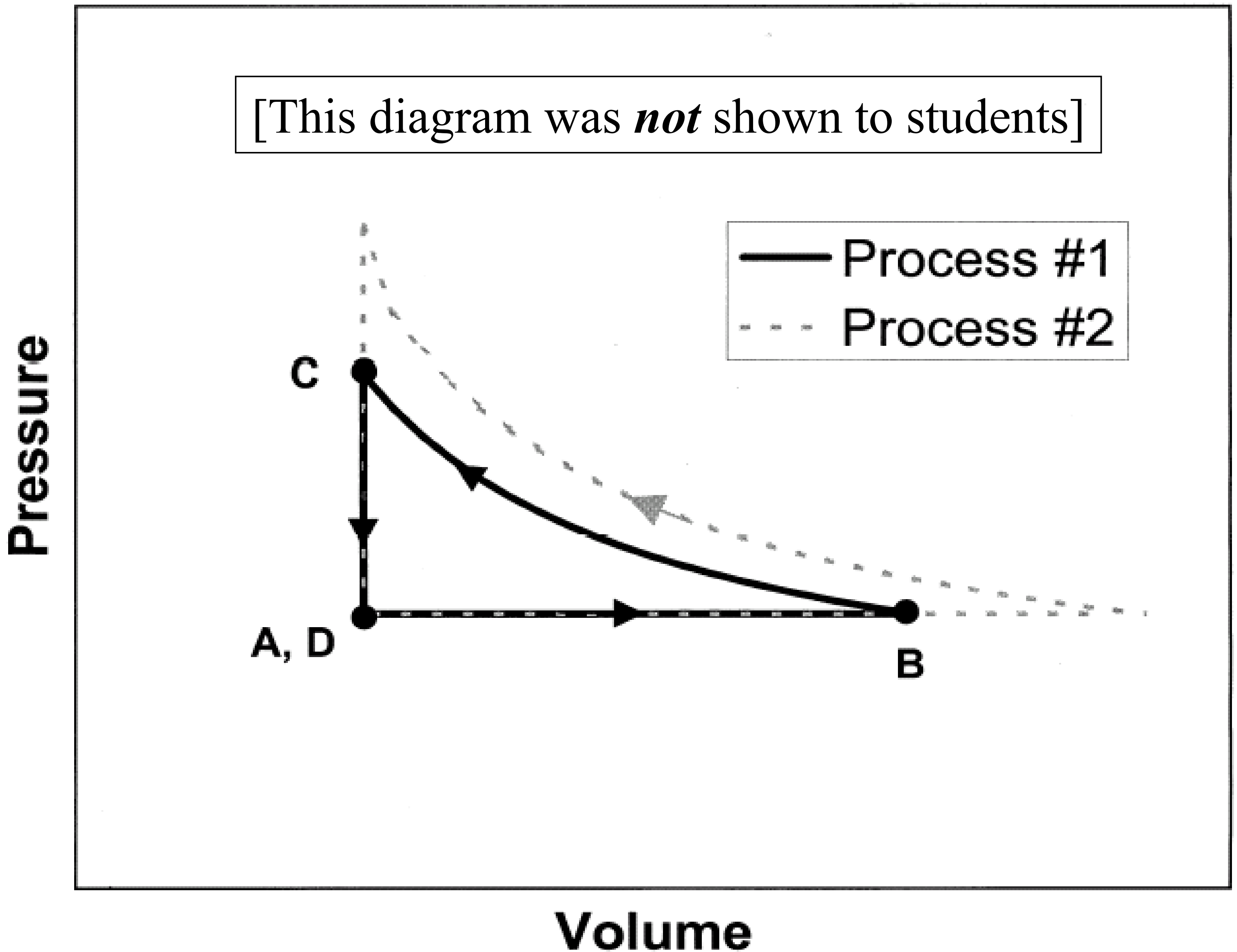
Time *D*

Piston in same position as at time *A*.

Temperature same as at time *A*.

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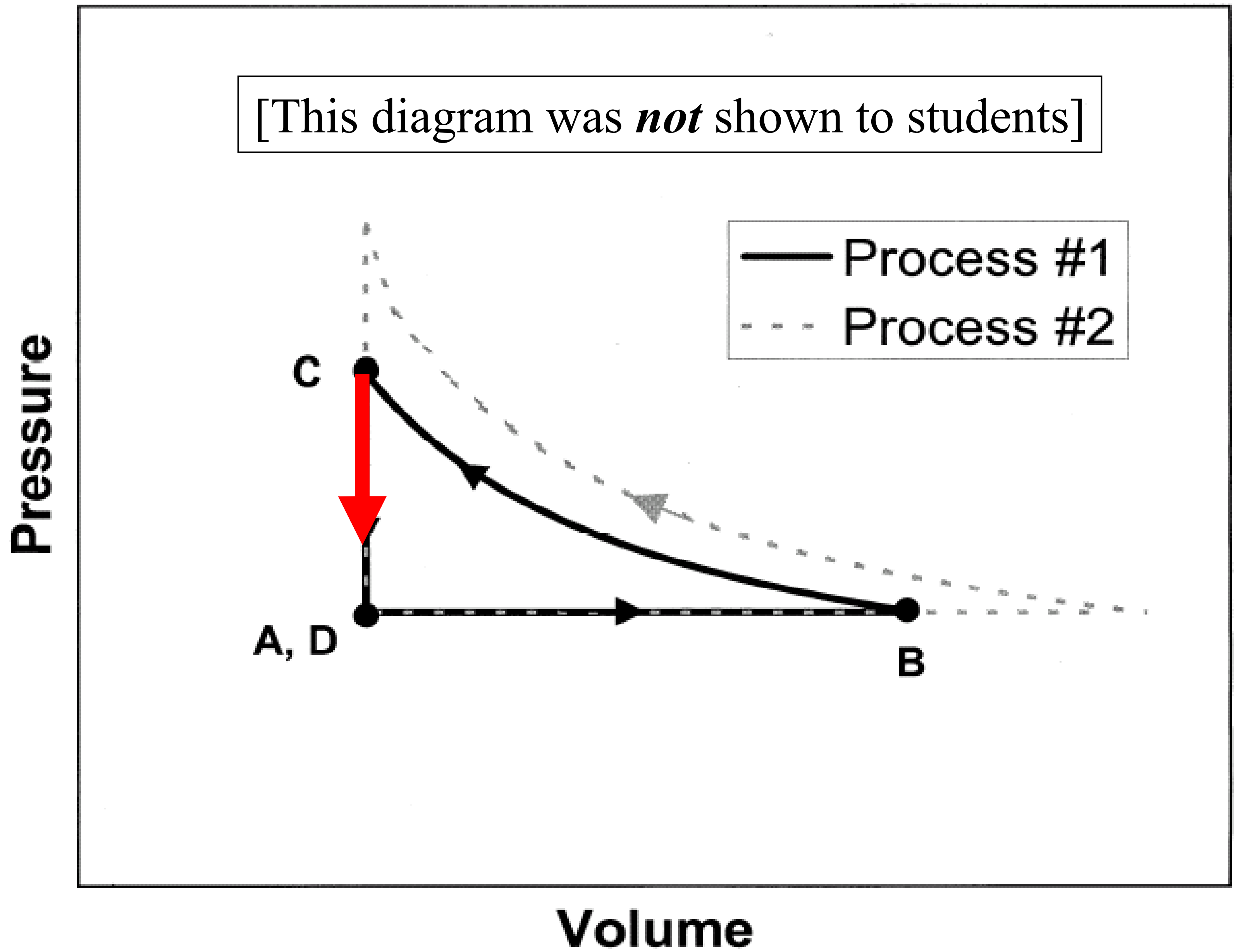
B
Pressure
Volume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Process #2
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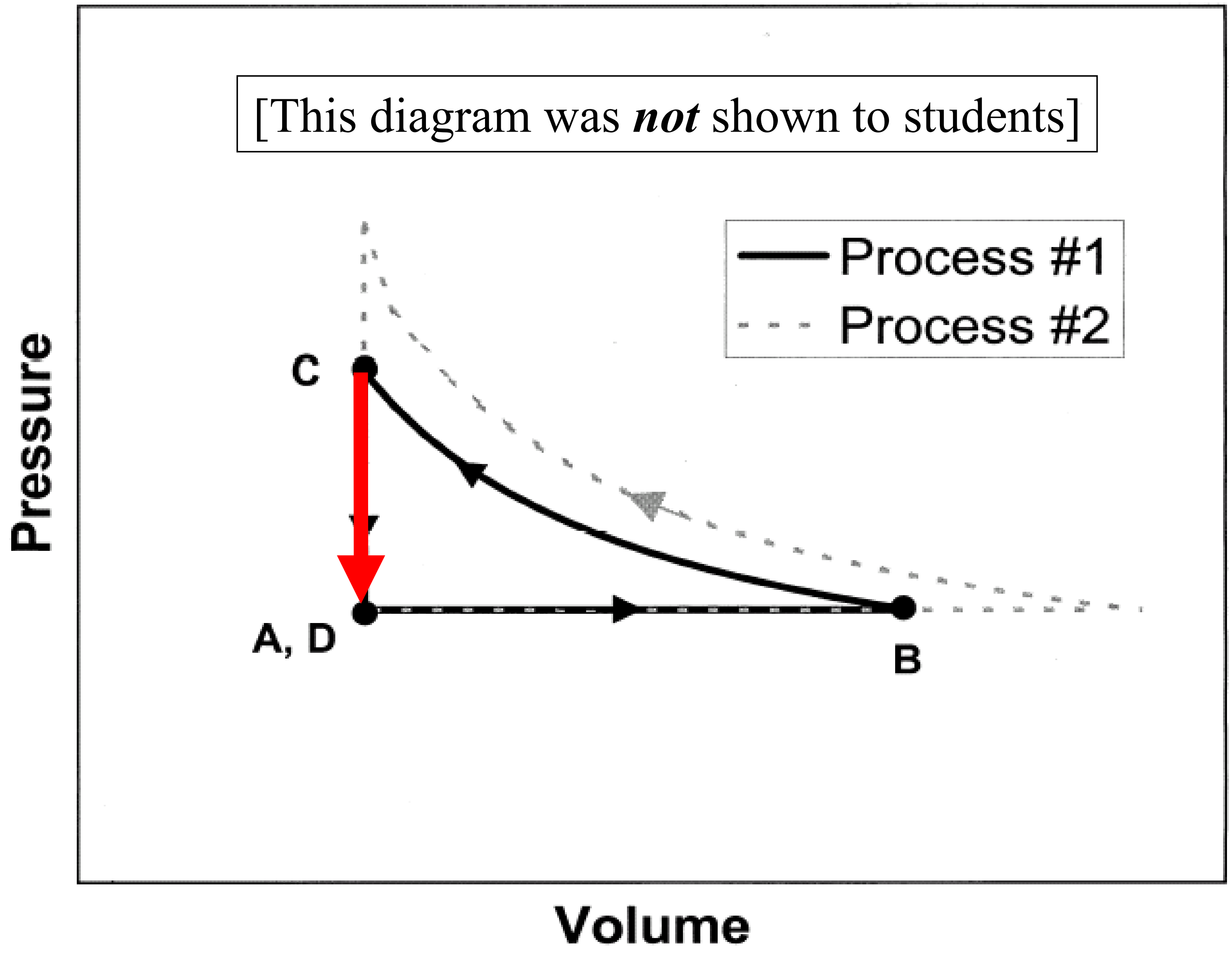
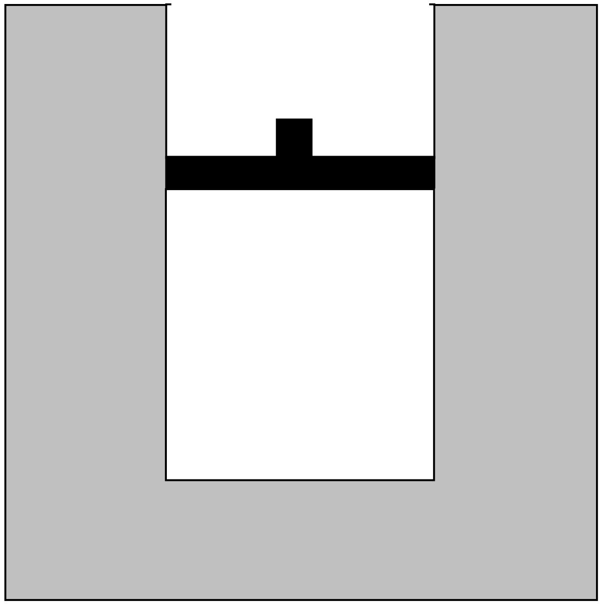
A, D
B
Pressure
Volume


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



Time *D*

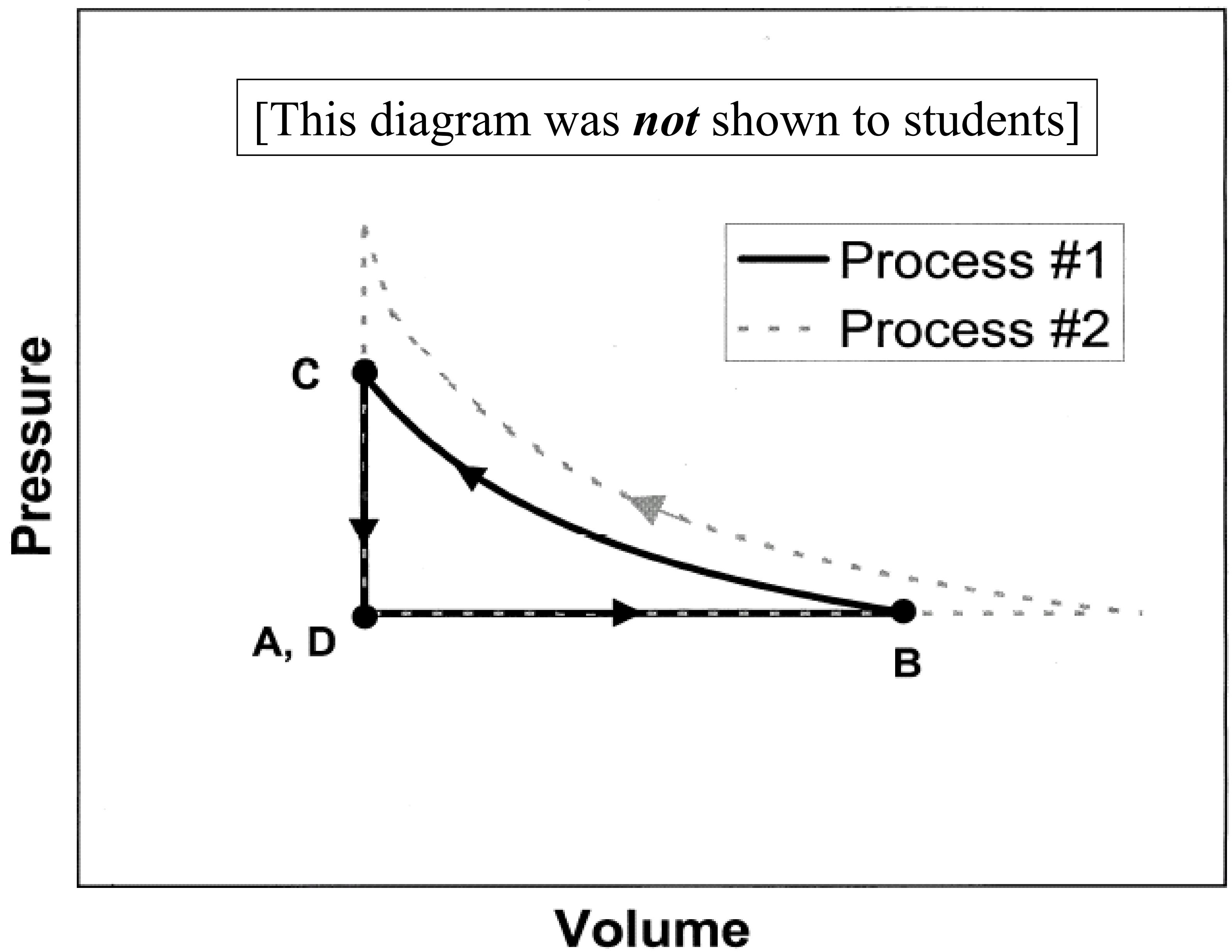
Piston in same position as at time *A*.

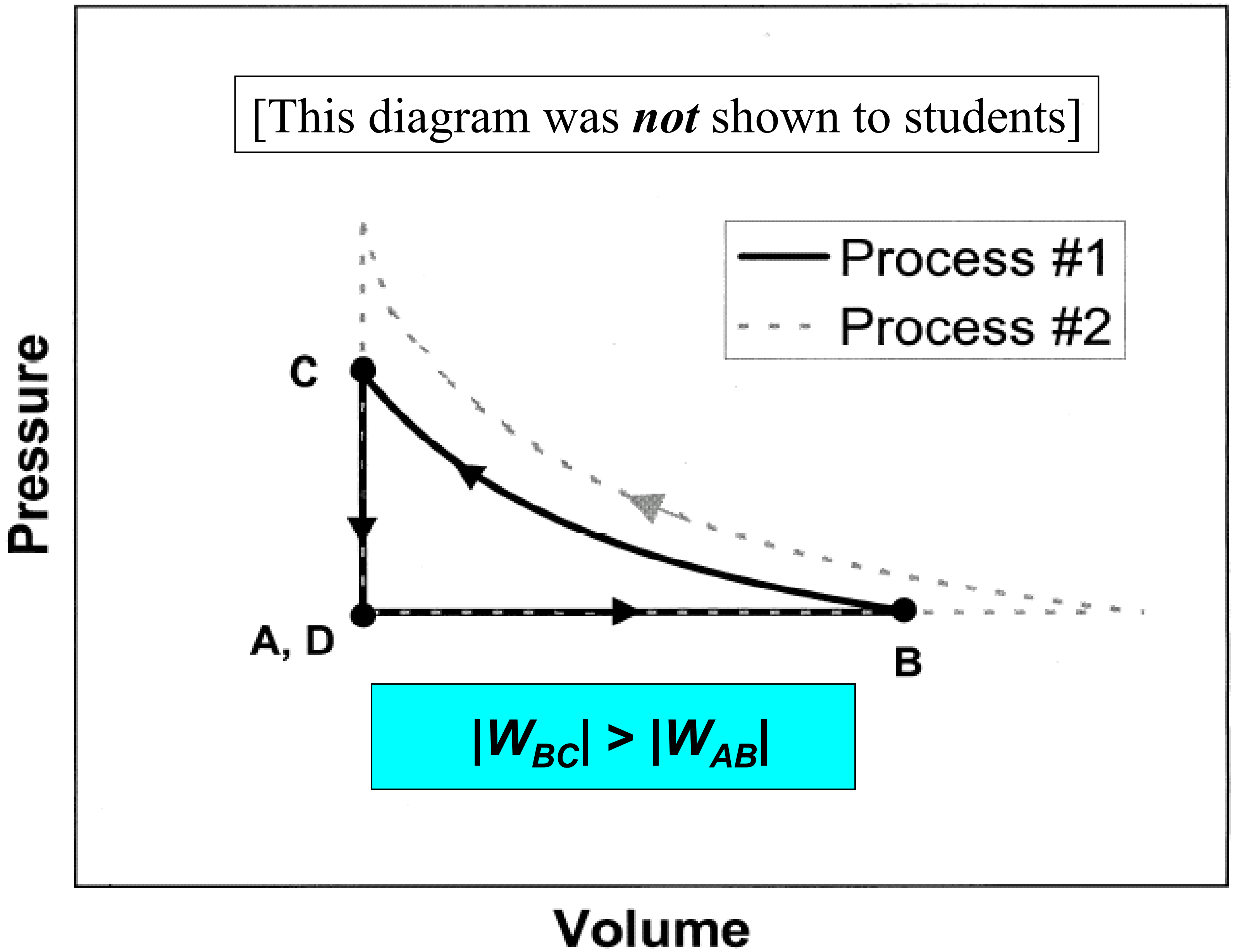
Temperature same as at time *A*.

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

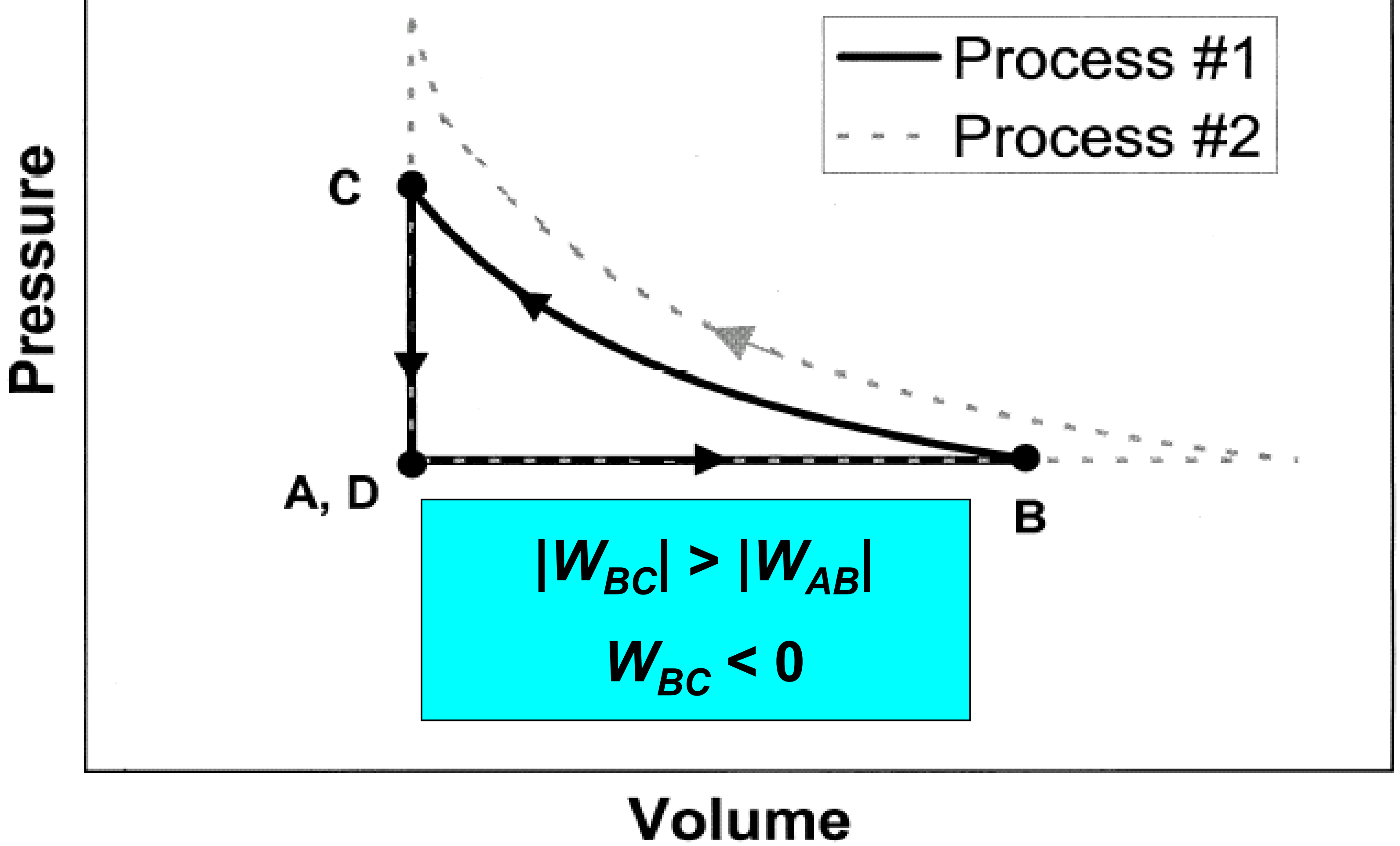
(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

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

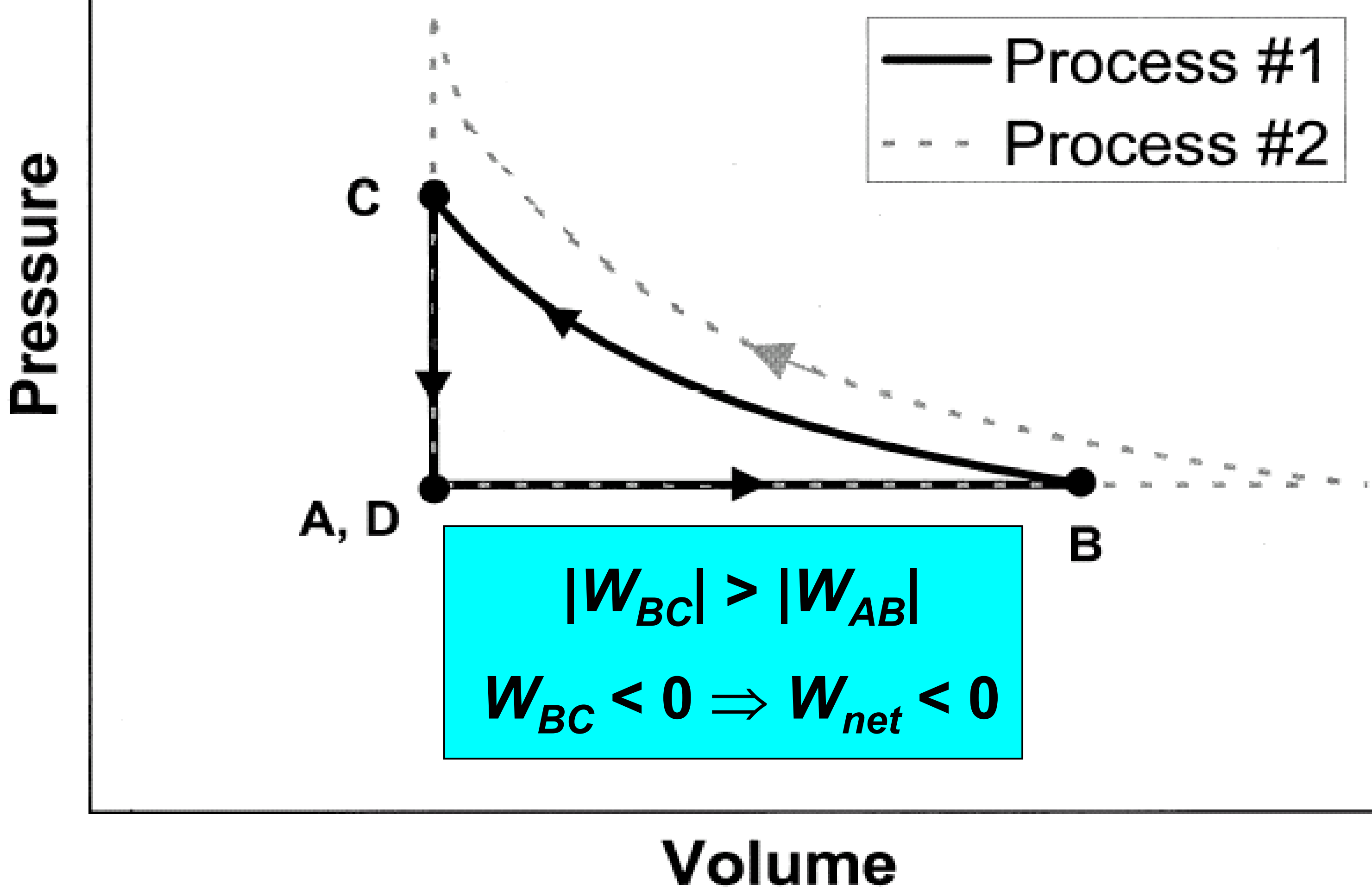

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume


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

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

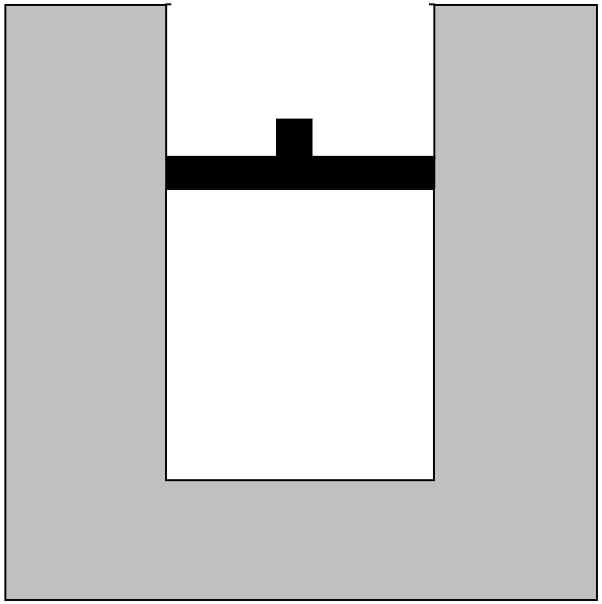


[This diagram was ***not*** shown to students]



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

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



Time *D*

Piston in same position as at time *A*.

Temperature same as at time *A*.

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

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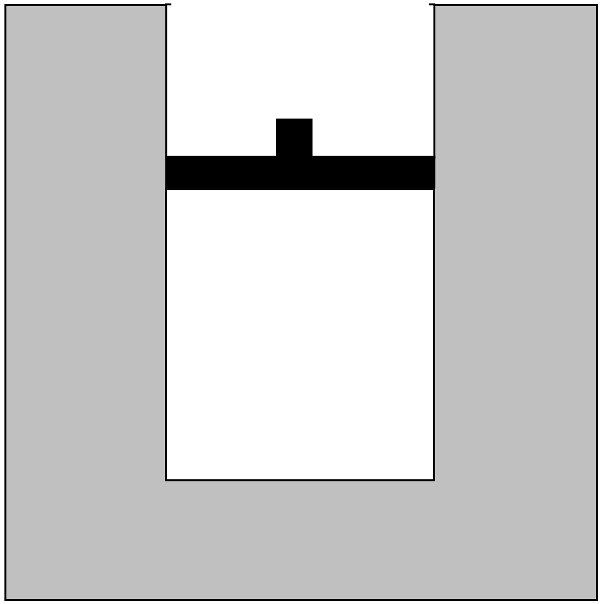

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Question #6: Consider ***the entire process*** from time *A* to time *D*.

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

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

Results on Interview Question #6 (i)

$N = 32$

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

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

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

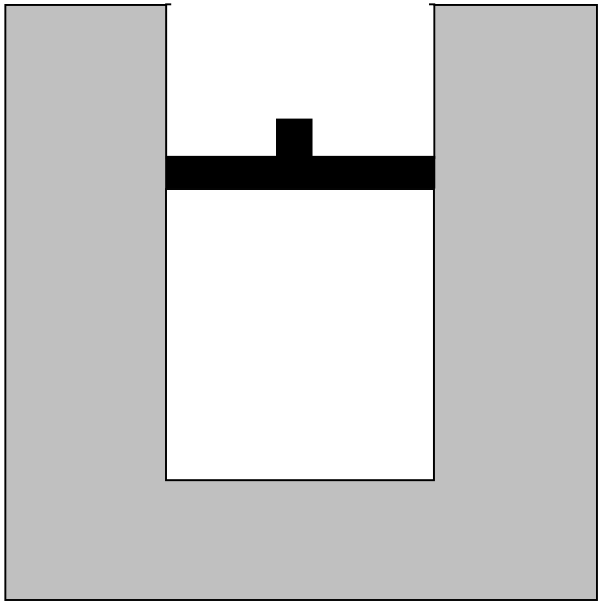
No response: 3%

Even after being asked to draw a *P-V* diagram for Process #1, 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*."

"[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*."



Time *D*

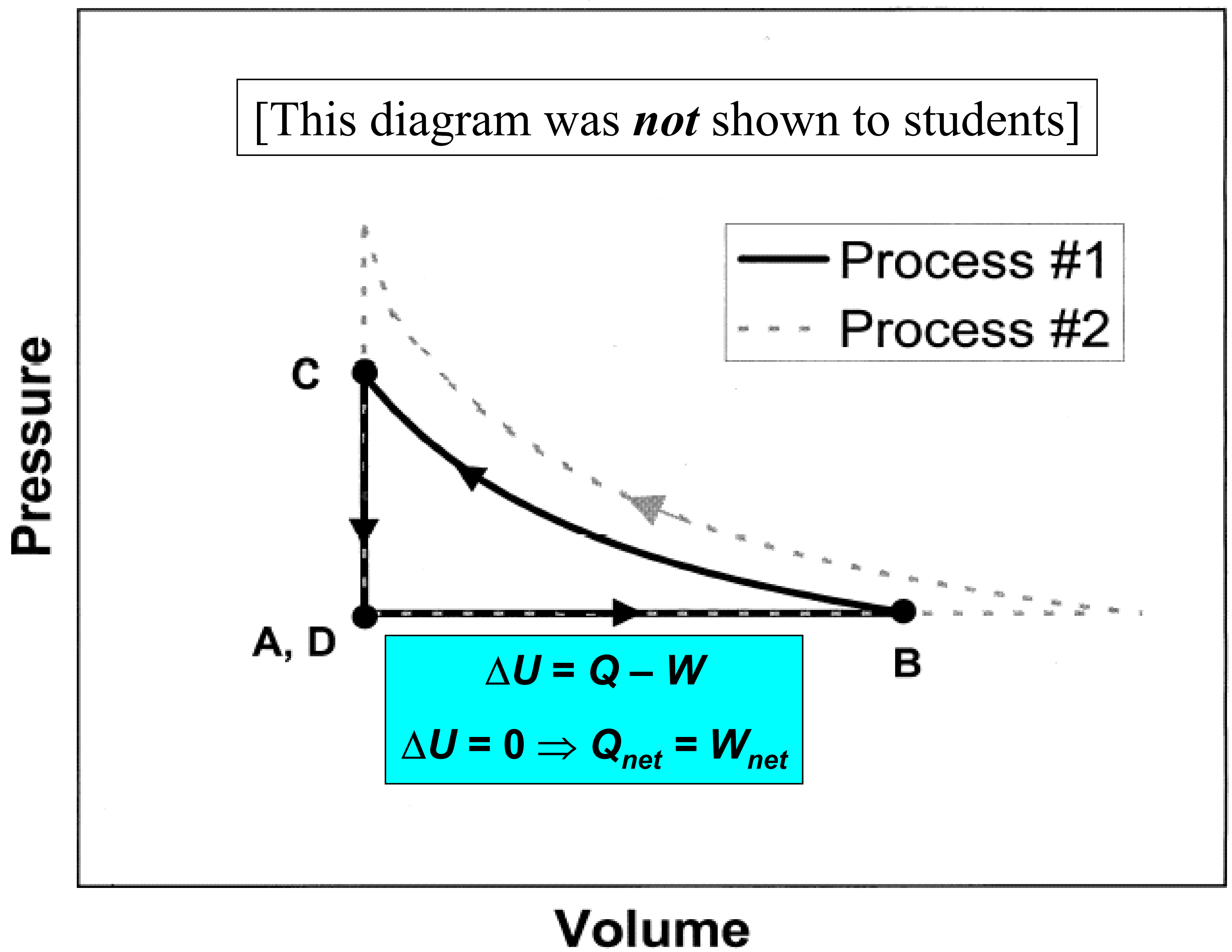
Piston in same position as at time *A*.

Temperature same as at time *A*.

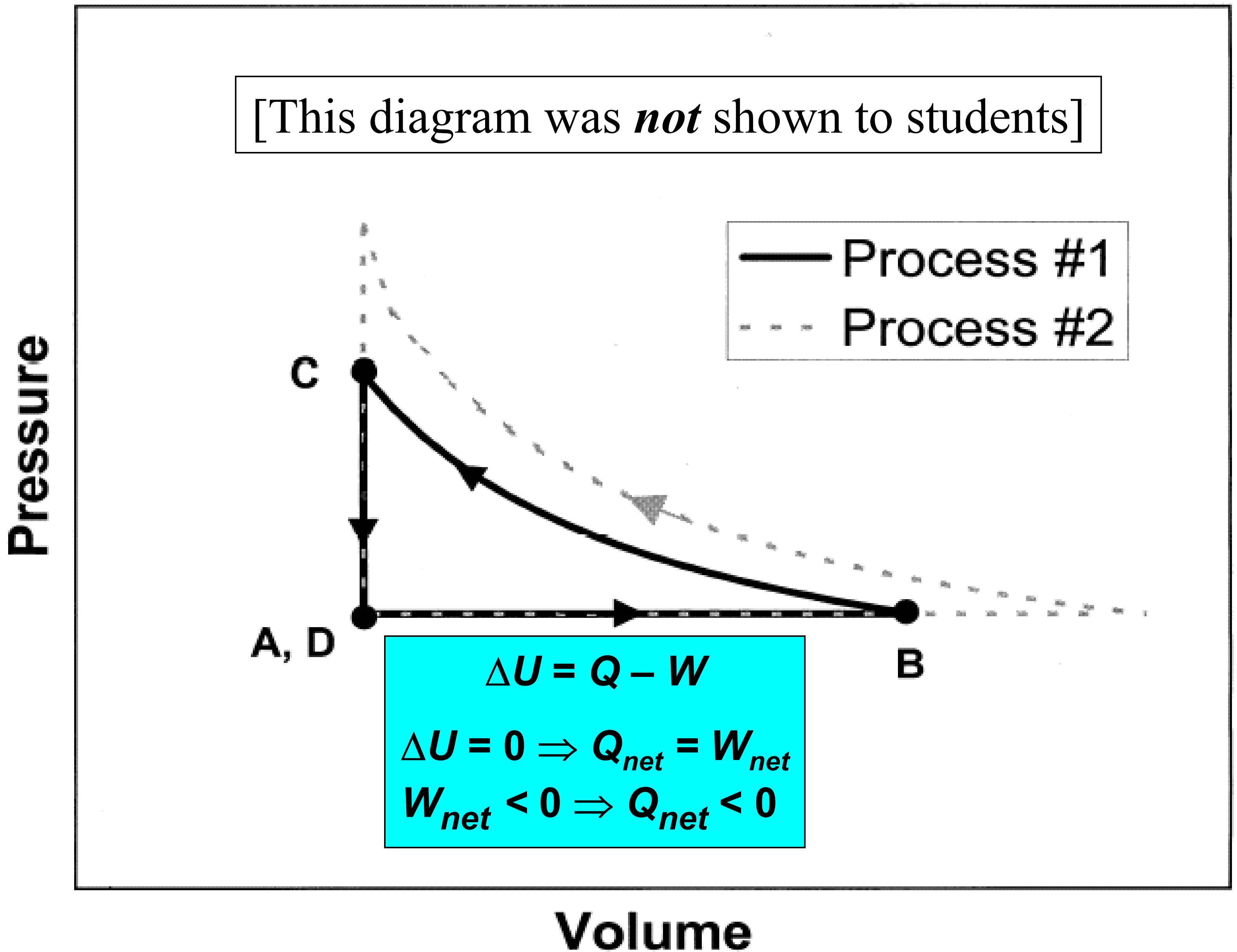
Question #6: Consider ***<u>the entire process</u>*** from time *A* to time *D*.

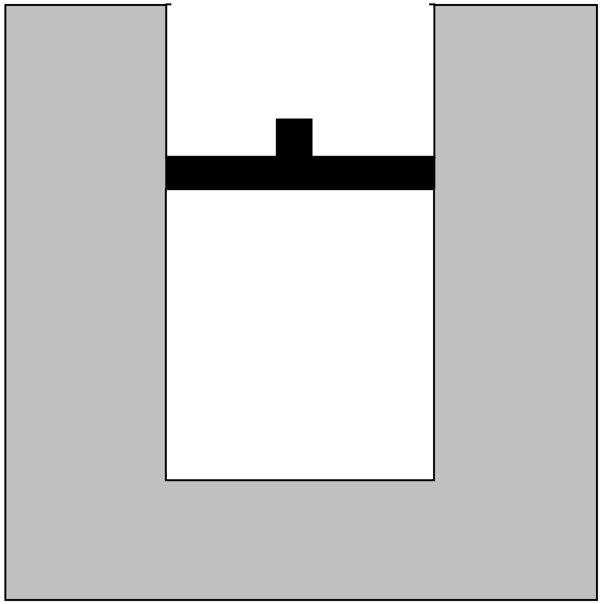
(i) Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

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



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


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



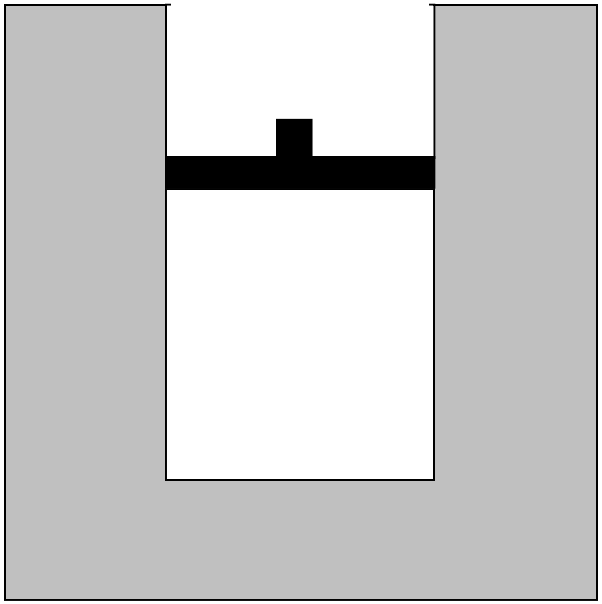
Time *D*

Piston in same position as at time *A*.

Temperature same as at time *A*.

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?



Time *D*

Piston in same position as at time *A*.

Temperature same as at time *A*.

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

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

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

Results on 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.

Explanations offered for $Q_{net} = 0$

"[Student #1] *The net heat absorbed is going to be zero. . . Same initial position, volume, pressure, number of molecules, same temperature. So even if it did absorb and lose some during the process, the ending result is equal to zero."*

"[Student #2] *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.*"

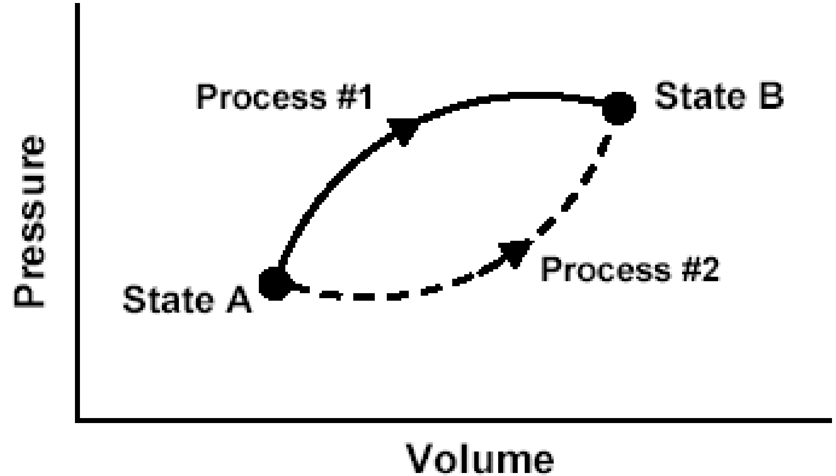
Most students thought that both Q_{net} and W_{net} are equal to zero

- 56% believed that both the net work done ***and*** the total heat transferred would be zero.
- Only three out of 32 students (9%) answered both parts of Interview Question #6 correctly.

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 absorbed by a system undergoing 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.]

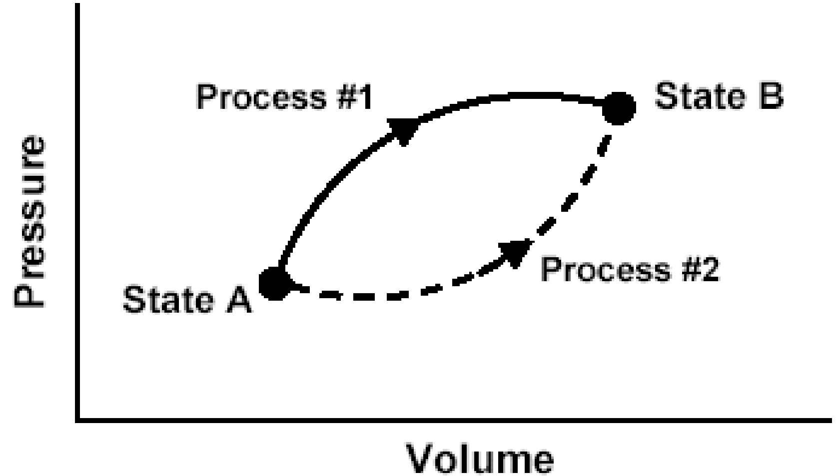
1. Is *W* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2? Explain.

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.



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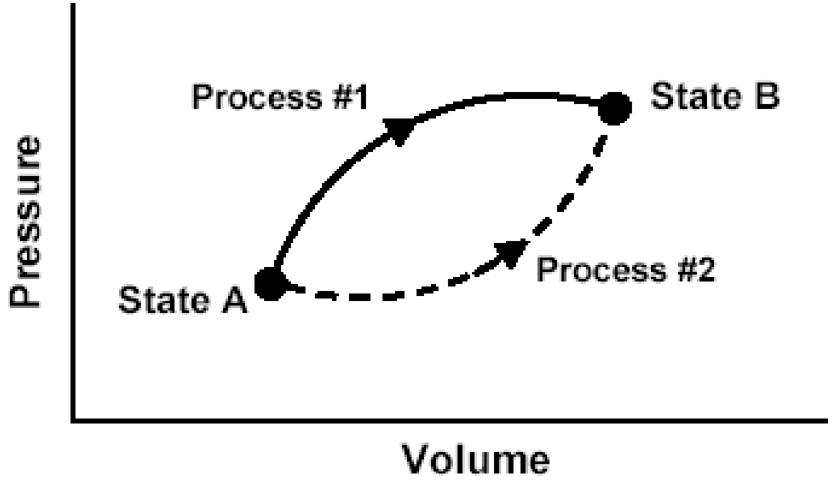
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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



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

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

2. Is Q for Process #1 $\boxed{\textit{\textbf{greater than}}}$, ***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?***

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)	**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*."

"Q *is greater for process 1 since* Q = U + W *and* W *is greater for process 1*."

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

Responses to Diagnostic Question #2
(Heat question)

	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002** Interview Sample (*N*=32)
$Q_1 > Q_2$	**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 15% of students responding to written diagnostic questions could explain why $Q_1 > Q_2$.
- Fewer than 20% of students in interview sample could explain why $Q_1 > Q_2$.
- 13% of students in interview sample were able to use first law to correctly answer Question #6(ii).

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

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

- Fewer than 15% of students responding to written diagnostic questions could explain why $Q_1 > Q_2$.
- Fewer than 20% of students in interview sample could explain why $Q_1 > Q_2$.
- 13% of students in interview sample were able to use first law to correctly answer Question #6(ii).

Students very often attribute state-function properties to process-dependent quantities.

Some Strategies for Instruction

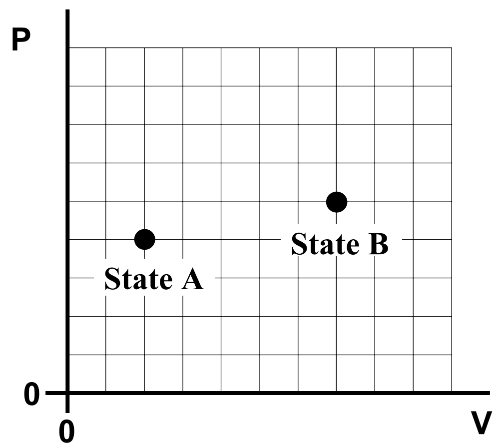
- Try to build on students' understanding of state-function concept.
- Focus on meaning of heat as ***transfer*** of energy, ***not*** quantity of energy residing in a system.
- Develop concept of work as energy transfer mechanism.

Thermodynamics Worksheet

For an ideal gas, the internal energy U is directly proportional to the temperature T. (This is because the internal energy is just the total kinetic energy of all of the gas molecules, and the temperature is defined to be equal to the *average* molecular kinetic energy.) For a monatomic ideal gas, the relationship is given by $U = \frac{3}{2}nRT$, where n is the number of moles of gas, and R is the universal gas constant.

1. Find a relationship between the internal energy of n moles of ideal gas, and pressure and volume of the gas. Does the relationship change when the number of moles is varied?

2. Suppose that m moles of an ideal gas are contained inside a cylinder with a movable piston (so the volume can vary). At some initial time, the gas is in state A as shown on the PV-diagram in Figure 1. A thermodynamic process is carried out and the gas eventually ends up in State B. Is the internal energy of the gas in State B *greater than*, *less than*, or *equal to* its internal energy in State A? (That is, how does U_B compare to U_A?) Explain.

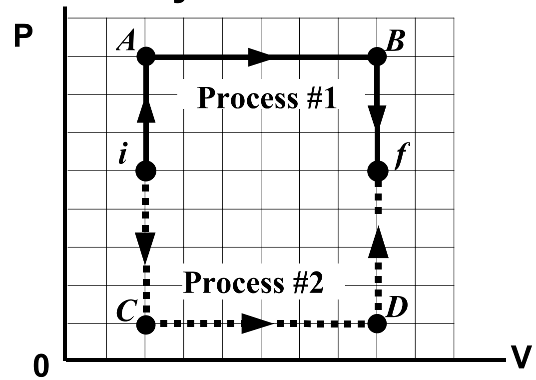


3. If a system starts with an initial internal energy of $U_{initial}$ and ends up with U_{final} some time later, we symbolize the *change* in the system's internal energy by ΔU and define it as follows: $\Delta U = U_{final} - U_{initial}$.

   a. For the process described in #2 (where the system goes from State A to State B), is ΔU for the gas system *greater than zero*, *equal to zero*, or *less than zero*?

   b. During this process, was there any energy transfer between the gas system and its surrounding environment? Explain.

Thermodynamics Worksheet



7. Rank the *temperature* of the gas at the six points *i*, *A*, *B*, *C*, *D*, and *f*. (Remember this is an *ideal* gas.)

8. Consider all sub-processes represented by straight-line segments. For each one, state whether the work is positive, negative, or zero. In the second column, rank all six processes according to their ΔU. (Pay attention to the sign of ΔU.) If two segments have the same ΔU, give them the same rank. In the last column, state whether heat is added *to* the gas, taken *away* from the gas, or is *zero* (i.e., *no* heat transfer). ***Hint:* First determine *U* for each point using the result of #1 on page 1.**

Process	**Is *W* +, –, or 0?**	**rank according to ΔU**	**heat added *to*, taken *away*, or *zero*?**
$i \to A$			
$A \to B$			
$B \to f$			
$i \to C$			
$C \to D$			
$D \to f$			

9. Consider **only** the sub-processes that have $W = 0$. Of these, which has the *greatest* absolute value of heat transfer *Q*? Which has the *smallest* absolute value of *Q*?

10. Rank the six segments in the table above according to the absolute value of their *W*. *Hint:* For processes at constant pressure, $W = P\,\Delta V$.

11. Using your answers to #8 and #10, explain whether W_1 is *greater than*, *less than*, or *equal to* W_2. [Refer to definitions, page 3.] Is there also a way to answer this question using an "area" argument?

12. Is Q_1 *greater than*, *less than*, or *equal to* Q_2? Explain. *Hint:* Compare the magnitude of ΔU_1 and ΔU_2, and make use of the answer to #6.

Outline

- Overview of goals and methods of PER

Investigation of Students' Reasoning:

- Students' reasoning in thermodynamics
- Diverse representational modes in student learning

Curriculum Development:

- Instructional methods and curricular materials for large-enrollment physics classes

Assessment of Instruction:

- Measurement of learning gain
- Potential broader impact of PER on undergraduate education

Investigation of Diverse Representational Modes in the Learning of Physics and Chemistry

NSF "Research on Learning and Education" program, Co-PI: T. J. Greenbowe

- Probe students' reasoning with widely used representations
  - e.g., free-body, *P-V*, and field-vector diagrams
- Compare student reasoning with different forms of representation of same concept
  - e.g., verbal, diagrammatic, mathematical/symbolic, graphical
- **Preliminary work:** student understanding of vector concepts
  - central to instruction in general physics curriculum
  - no previous studies probed vectors in graphical context

Physics Students' Understanding of Vector Concepts

N. Nguyen and DEM, Am. J. Phys. (in press)

- Seven-item quiz administered in all ISU general physics courses during 2000-2001
- Quiz items focus on basic vector concepts posed in graphical form
- Given during first week of class; 2031 responses received
  - Algebra-based course:
    A-1, N = 520; A-2, N = 201
  - Calculus-based course:
    C-1, N = 608; C-2, N = 702

A-1: First semester,
algebra-based course

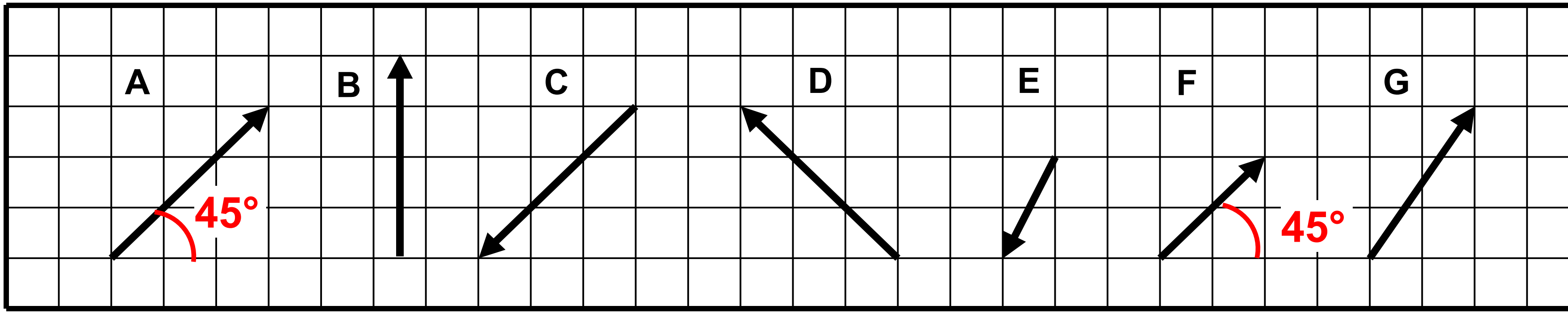
A-2: Second semester,
algebra-based course

etc.

Two Key Items

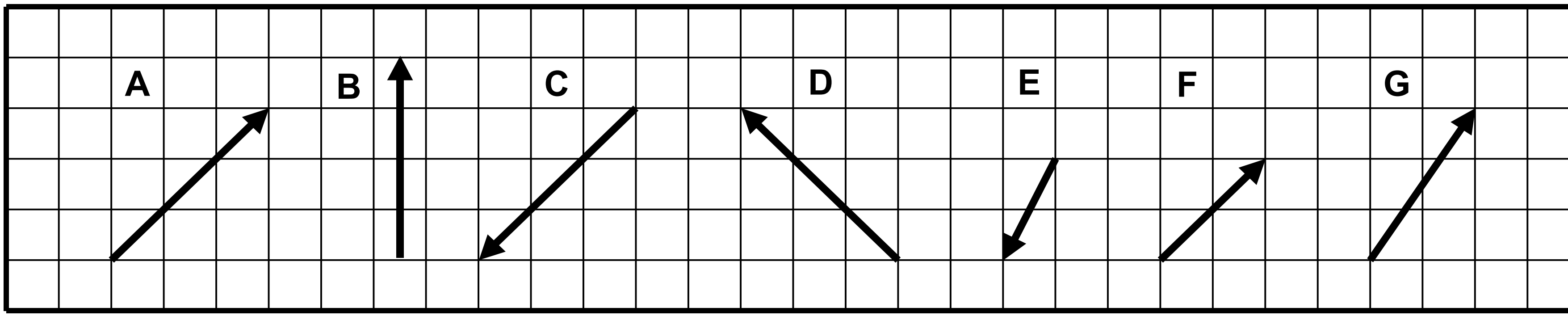
- **Question #2:** Choose vector with same direction as given vector
- **Question #5:** Two-dimensional vector addition

2. List all the vectors that have the same **direction** as the first vector listed, $\vec{\mathbf{A}}$. If there are none, please explain why.



Direction of **F** is same as direction of **A**

2. List all the vectors that have the same **direction** as the first vector listed, $\vec{\mathbf{A}}$. If there are none, please explain why.

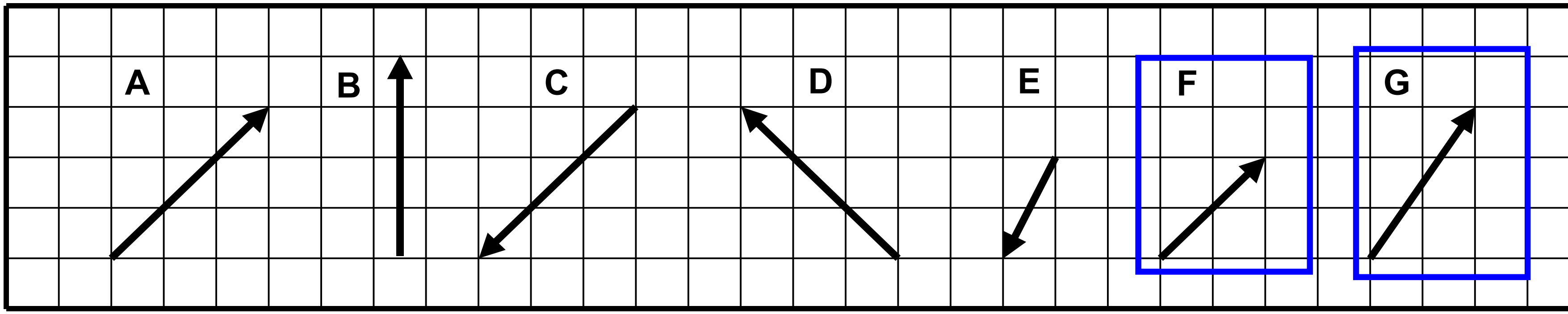


Error Rates (incorrect responses):

C-2: ***23%*** **C-1**: ***29%***

A-2: ***37%*** **A-1**: ***45%***

2. List all the vectors that have the same **direction** as the first vector listed, $\vec{\mathbf{A}}$. If there are none, please explain why.



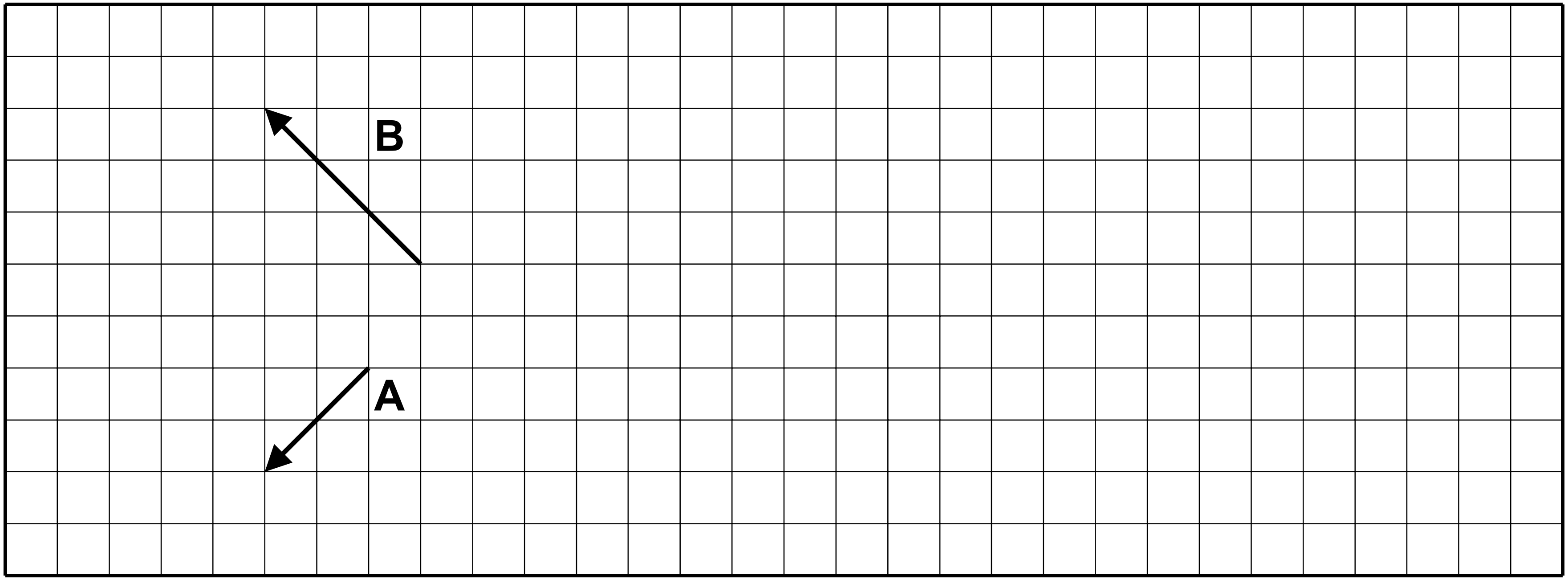
Most common error: choosing **F** ***and*** **G**

Two Key Items

- **Question #2:** Choose vector with same direction as given vector

- **Question #5:** Two-dimensional vector addition

5. In the figure below there are two vectors $\vec{\mathbf{A}}$ and $\vec{\mathbf{B}}$. Draw a vector $\vec{\mathbf{R}}$ that is the sum of the two, (i.e. $\vec{\mathbf{R}} = \vec{\mathbf{A}} + \vec{\mathbf{B}}$). Clearly label the resultant vector as $\vec{\mathbf{R}}$.



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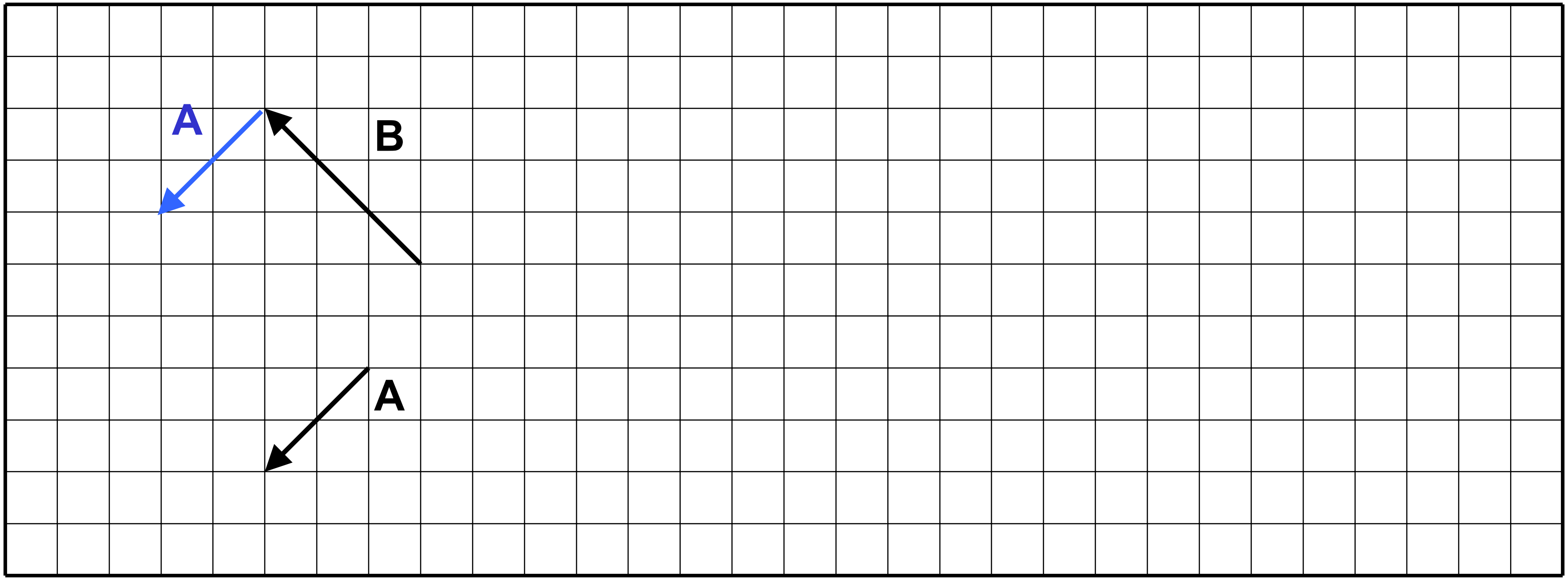

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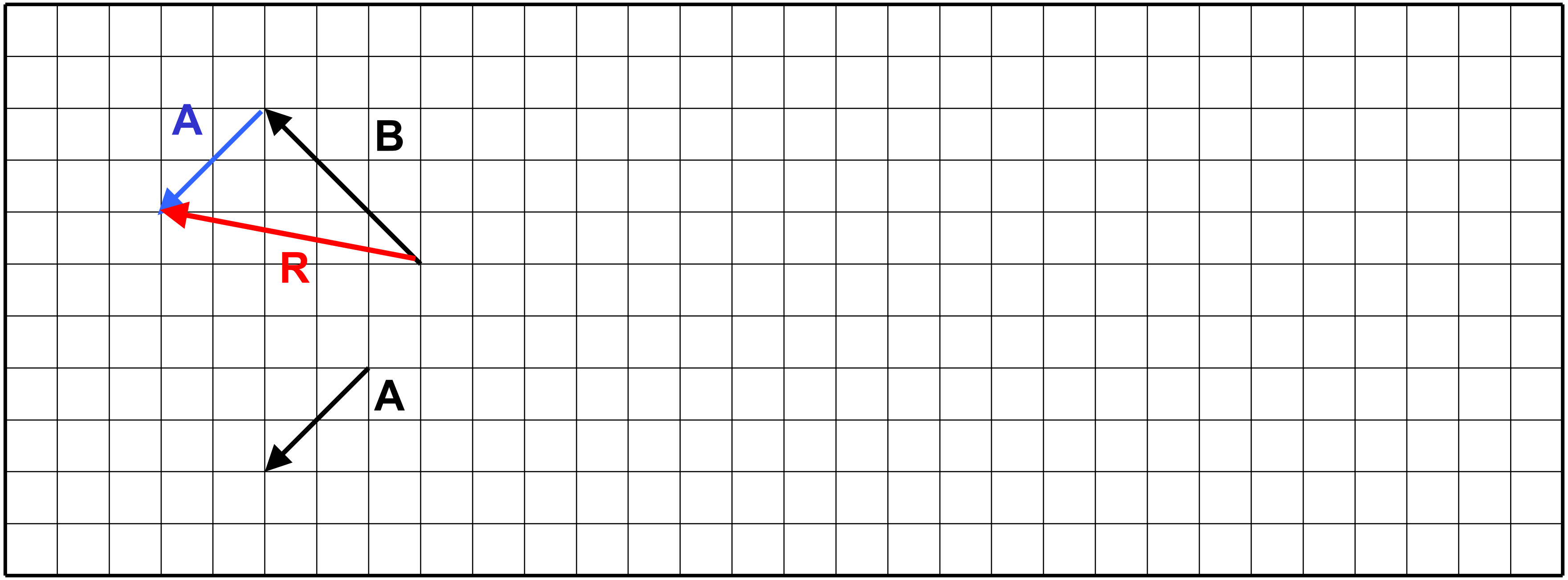

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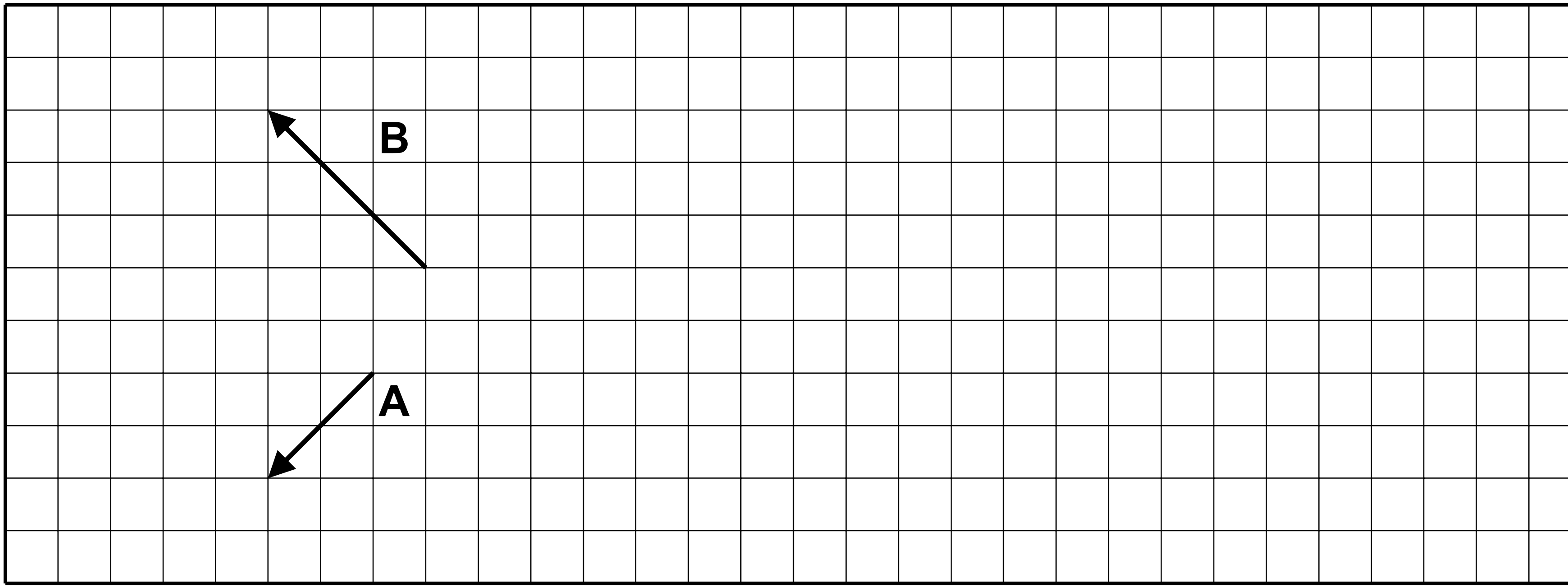
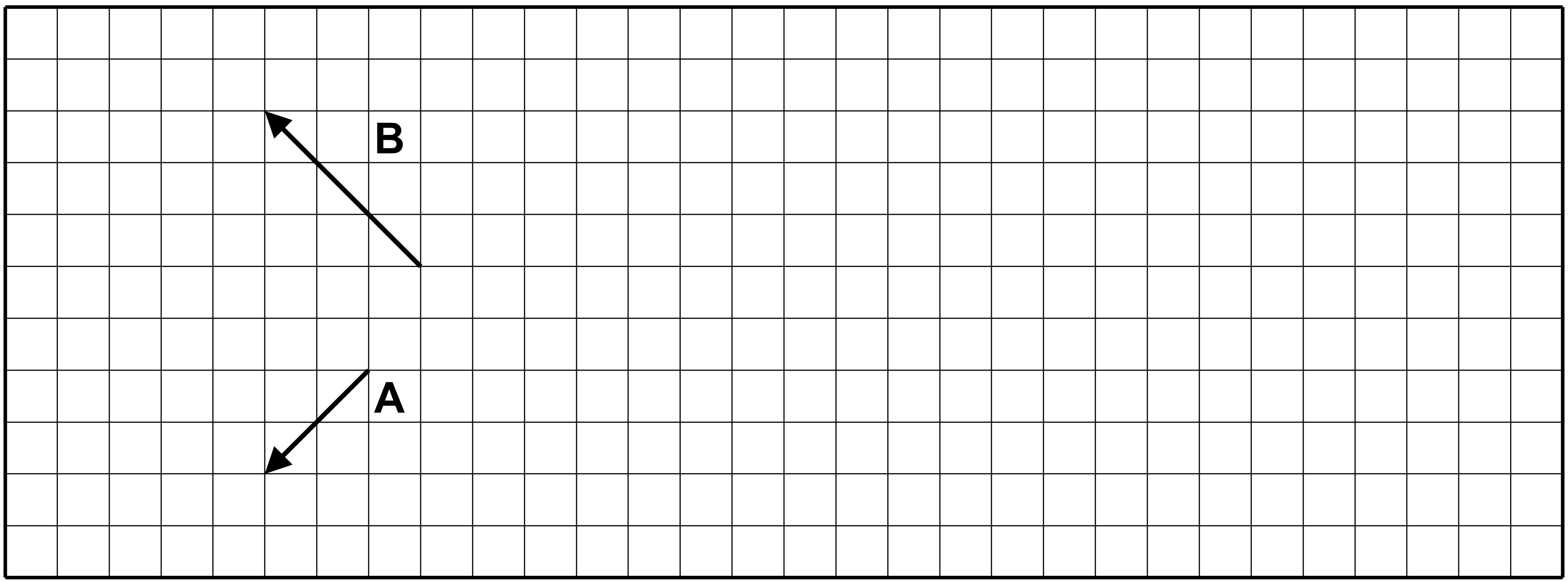


Error Rates:

C-2: *27%* **C-1**: *42%*

A-2: *56%* **A-1**: *78%*

5. In the figure below there are two vectors $\vec{\mathbf{A}}$ and $\vec{\mathbf{B}}$. Draw a vector $\vec{\mathbf{R}}$ that is the sum of the two, (i.e. $\vec{\mathbf{R}} = \vec{\mathbf{A}} + \vec{\mathbf{B}}$). Clearly label the resultant vector as $\vec{\mathbf{R}}$.



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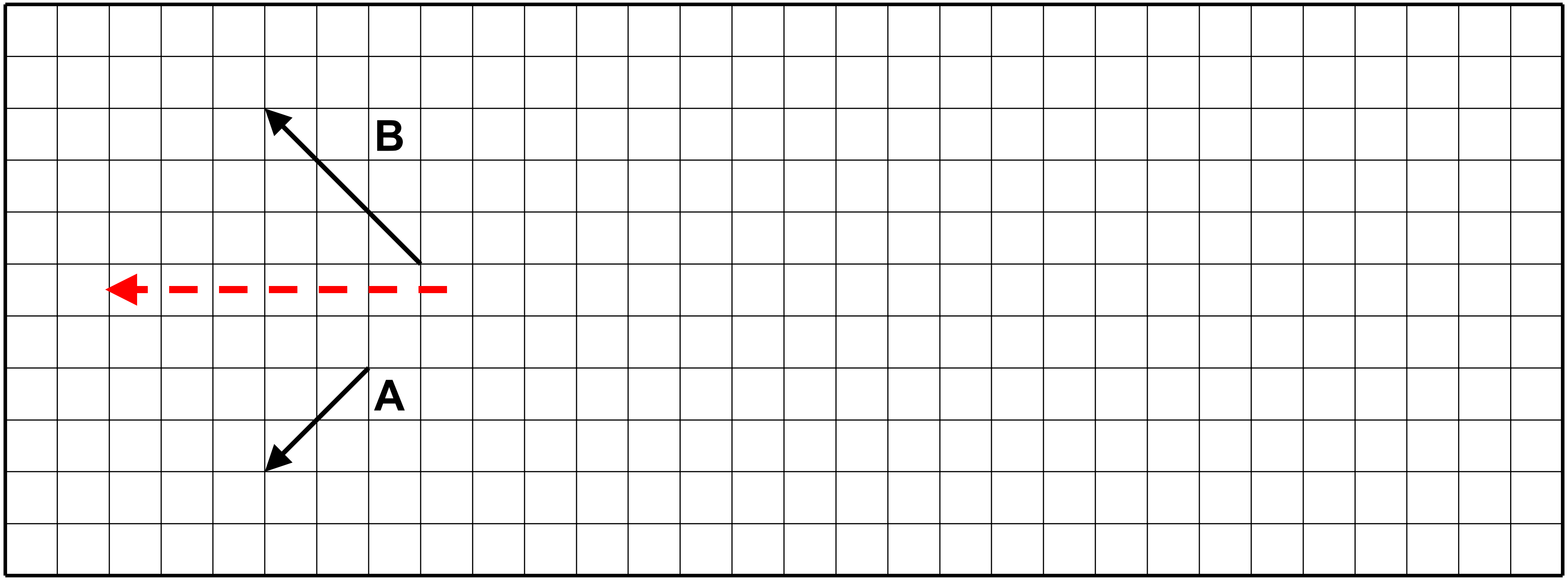
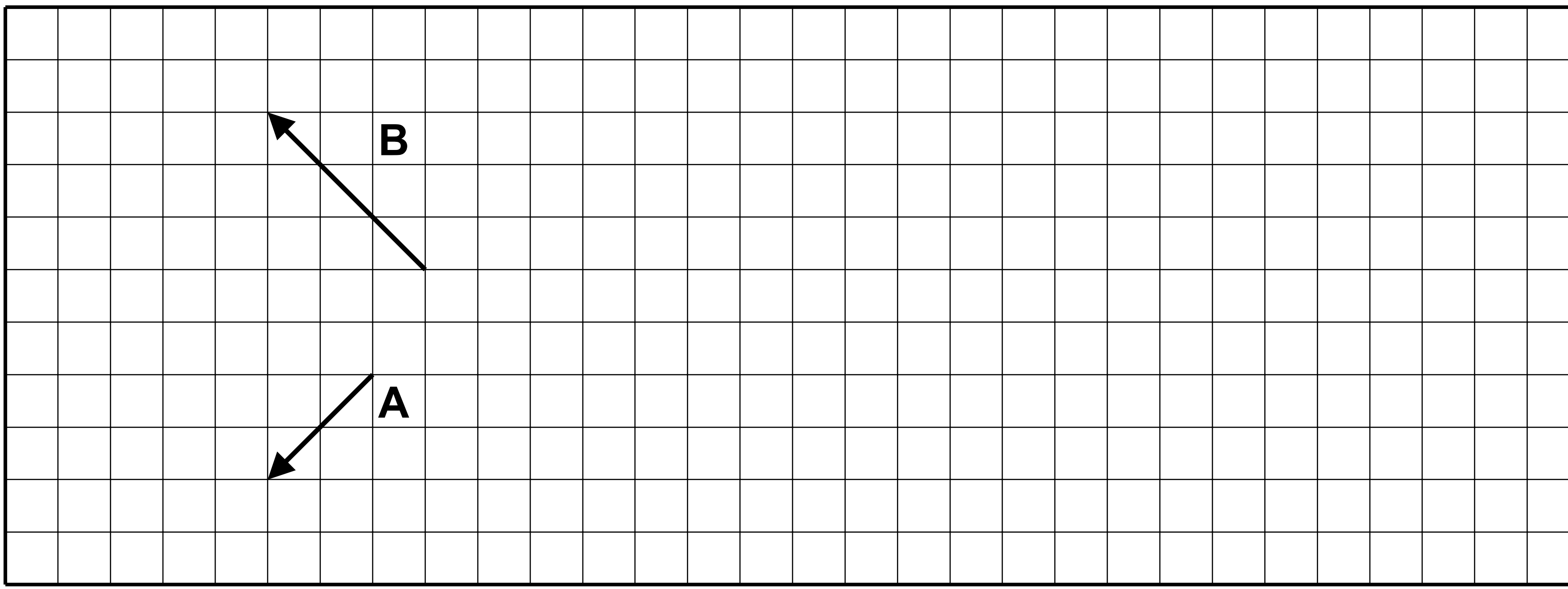


Common Error

5. In the figure below there are two vectors $\vec{\mathbf{A}}$ and $\vec{\mathbf{B}}$. Draw a vector $\vec{\mathbf{R}}$ that is the sum of the two, (i.e. $\vec{\mathbf{R}} = \vec{\mathbf{A}} + \vec{\mathbf{B}}$). Clearly label the resultant vector as $\vec{\mathbf{R}}$.



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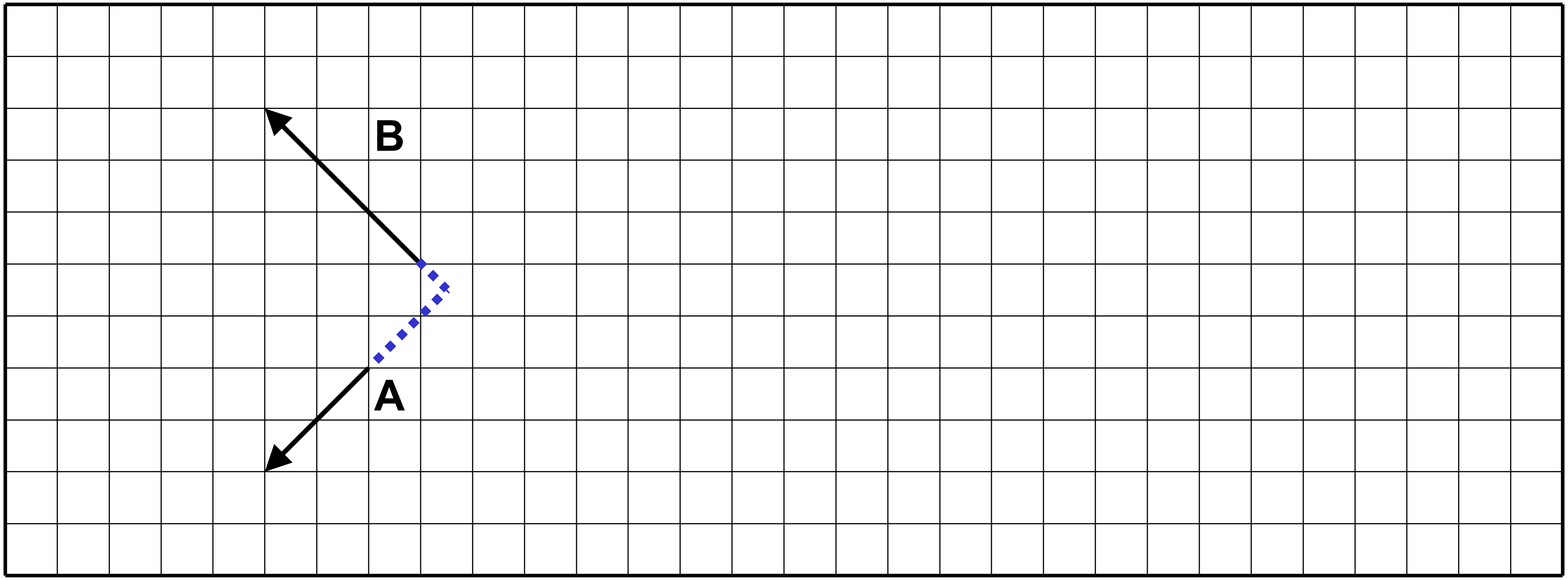

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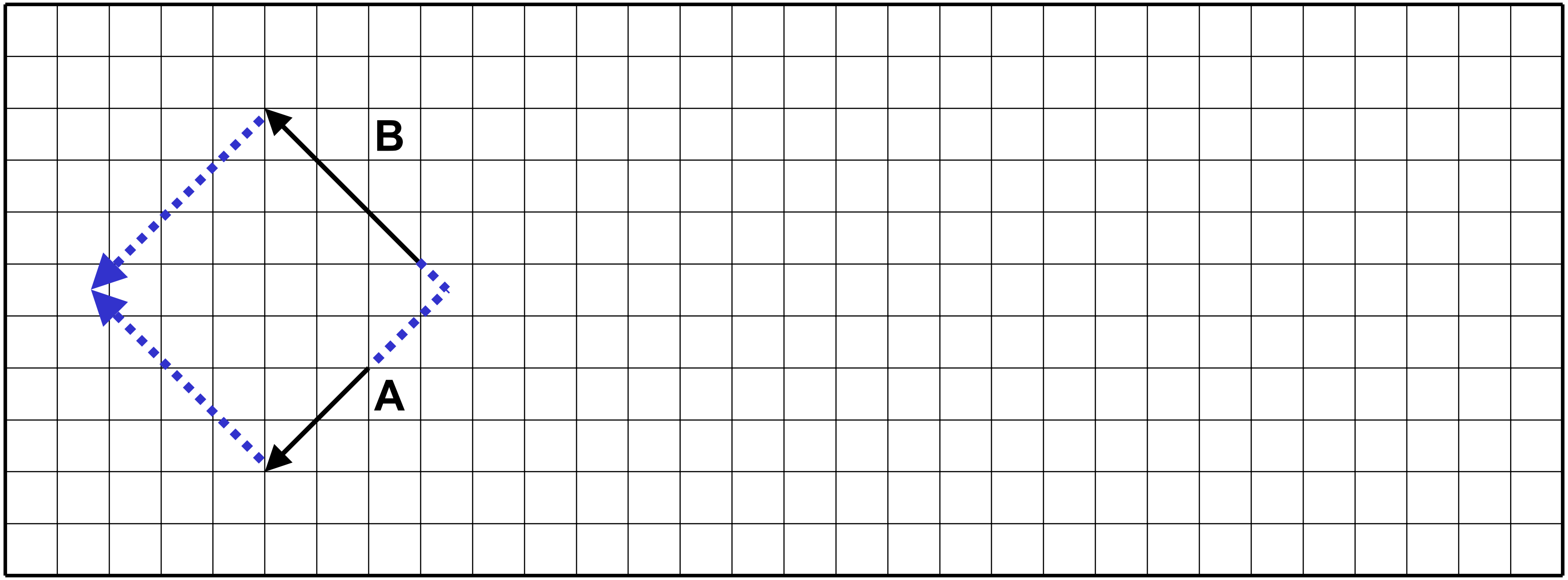

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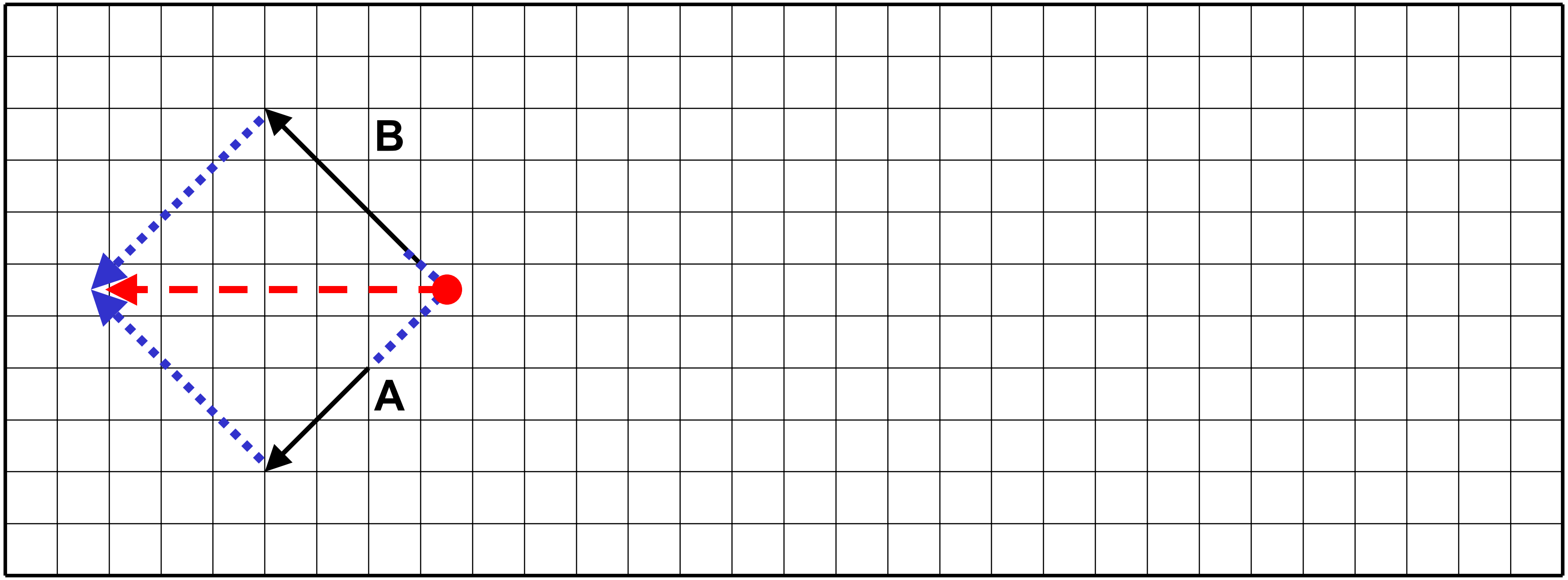


Common Incorrect Method

Difficulties with Vector Concepts

- Imprecise understanding of vector direction
- Vague notion of vector addition

  "***R*** should be a combination of ***A*** and ***B*** so I tried to put it between ***A*** and ***B***"

- Confusion regarding parallel transport

  (must maintain magnitude ***and*** direction as vector "slides")

Difficulties with Graphical Representation of Vectors

- **Dependence on grid:** many students were unable to add vectors without a grid
- **Little gain:** Relatively small gains resulting from first-semester instruction

Investigation of Physics Learning with Diverse Representations

(with T. Greenbowe and L. Allen)

- Probe student understanding of standard physics representations
- Compare student reasoning with different forms of representation

“Multiple-Representation” Quiz

- Same or similar question asked in more than one form of representation
  - e.g., verbal [words only], diagrammatic, mathematical, etc.
- Comparison of responses yields information on students’ reasoning patterns with diverse representations

Example: Quiz on Gravitation

- 11-item quiz given on second day of class in Physics 112 (second-semester, algebra-based general physics)
  - all students have completed study of mechanics
- Two questions on quiz relate to Newton’s third law in astronomical context
  - verbal version and diagrammatic version

#1. The mass of the sun is about 3×10^5 times the mass of the earth. How does the magnitude of the gravitational force exerted by the sun on the earth compare with the magnitude of the gravitational force exerted by the earth on the sun?

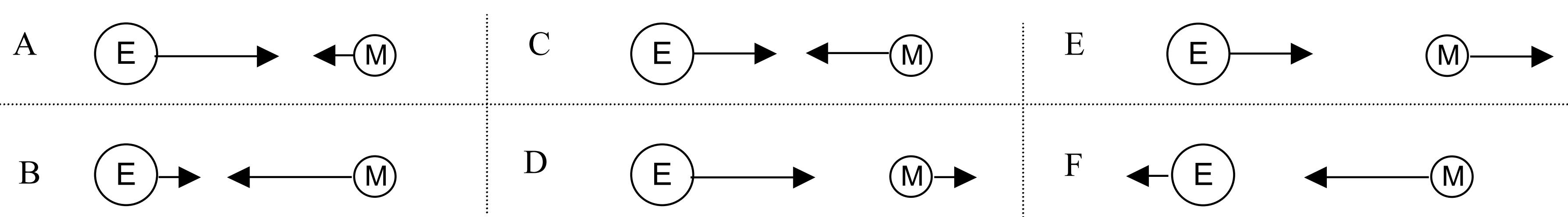
The force exerted by the sun on the earth is:

A. about 9×10^{10} times larger
B. about 3×10^5 times larger
C. exactly the same
D. about 3×10^5 times smaller
E. about 9×10^{10} times smaller

"verbal"

#8. Which of these diagrams most closely represents the gravitational forces that the earth and moon exert ***on each other***? (Note: The mass of the earth is about 80 times larger than that of the moon.)

"diagrammatic"

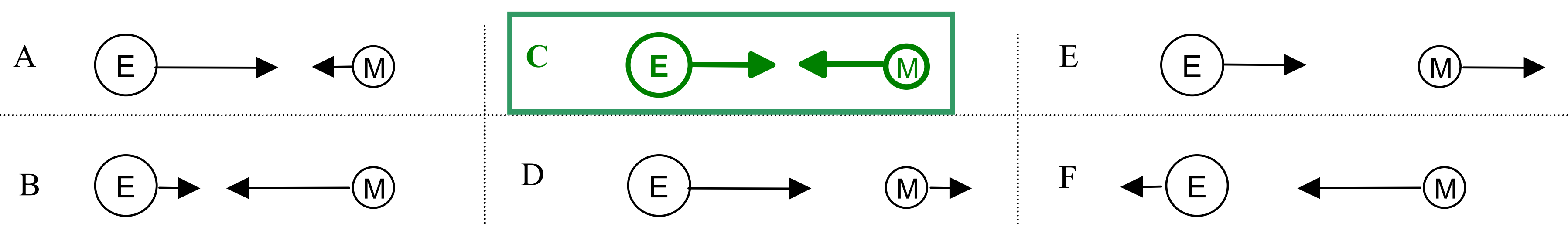


#1. The mass of the sun is about 3×10^5 times the mass of the earth. How does the magnitude of the gravitational force exerted by the sun on the earth compare with the magnitude of the gravitational force exerted by the earth on the sun?

The force exerted by the sun on the earth is:

A. about 9×10^{10} times larger
B. about 3×10^5 times larger
C. exactly the same
D. about 3×10^5 times smaller
E. about 9×10^{10} times smaller

#8. Which of these diagrams most closely represents the gravitational forces that the earth and moon exert ***on each other***? (Note: The mass of the earth is about 80 times larger than that of the moon.)



#1. The mass of the sun is about 3×10^5 times the mass of the earth. How does the magnitude of the gravitational force exerted by the sun on the earth compare with the magnitude of the gravitational force exerted by the earth on the sun?

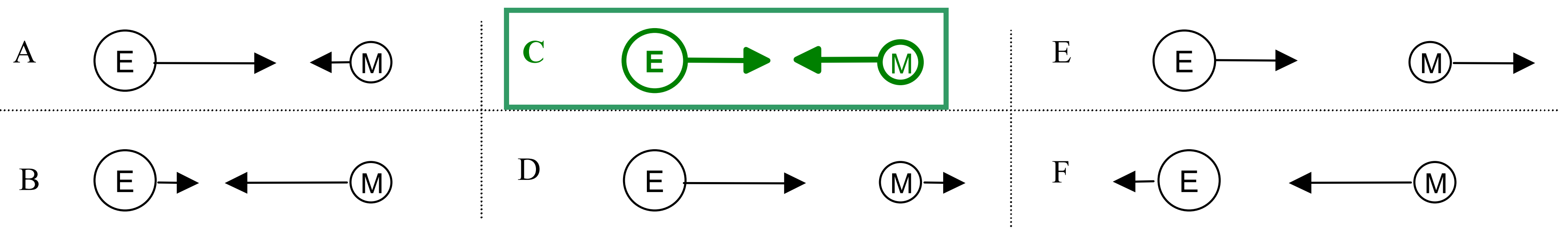
The force exerted by the sun on the earth is:

A. about 9×10^{10} times larger
B. about 3×10^5 times larger
C. exactly the same
D. about 3×10^5 times smaller
E. about 9×10^{10} times smaller

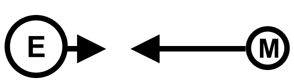
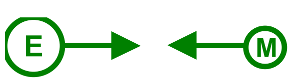
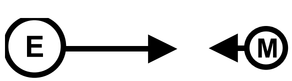
Results of Quiz on Gravitation

	1998	1999	2000	2001	2002
#1. force by sun is:	*N= 78*	*N = 96*	*N = 83*	*N = 77*	*N = 74*
larger					
*** the same**	**14%**	**10%**	**20%**	**23%**	**14%**
smaller					

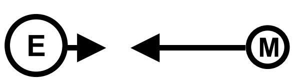
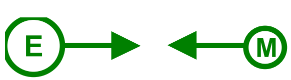
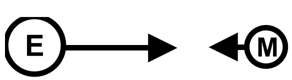
#8. Which of these diagrams most closely represents the gravitational forces that the earth and moon exert ***on each other***? (Note: The mass of the earth is about 80 times larger than that of the moon.)



Results of Quiz on Gravitation

	1998	1999	2000	2001	2002
#1. force by sun is:	*N= 78*	*N = 96*	*N = 83*	*N = 77*	*N = 74*
larger					
*** the same**	**14%**	**10%**	**20%**	**23%**	**14%**
smaller					
#8. earth/moon force					
					
* 	**6%**	**6%**	**12%**	**12%**	**7%**
					

Results of Quiz on Gravitation

	1998	1999	2000	2001	2002
#1. force by sun is:	*N= 78*	*N = 96*	*N = 83*	*N = 77*	*N = 74*
larger	**81%**	**83%**	**76%**	**70%**	**84%**
*** the same**	**14%**	**10%**	**20%**	**23%**	**14%**
smaller	**5%**	**6%**	**4%**	**6%**	**3%**
#8. earth/moon force					
	**54%**	**45%**	**45%**	**55%**	**43%**
* 	**6%**	**6%**	**12%**	**12%**	**7%**
	**38%**	**47%**	**41%**	**34%**	**46%**
[wrong direction]	1%	2%	2%	0%	4%

Comparison of Responses

- Proportion of correct responses on diagrammatic version of question is consistently lower than on verbal version.

- Pattern of incorrect responses is dramatically different on two versions of question:

  – most common response on verbal version: *force exerted by more massive object has larger magnitude*

  – on diagrammatic version: *force exerted by more massive* ***or*** *less massive object has larger magnitude*

Comparison of Responses: Diagrammatic vs. Verbal

ratio of:	1998	1999	2000	2001	2002	Phys 222 (Calc) $N = 240$
$\dfrac{correct\ on\ \#8\ (diagrammatic)}{correct\ on\ \#1\ (verbal)}$	0.45	0.60	0.59	0.50	0.50	0.61
$\dfrac{\text{"}smaller\text{"}\ on\ \#8\ (diagrammatic)}{\text{"}smaller\text{"}\ on\ \#1\ (verbal)}$	8	8	11	5	18	26

→ Apparently many students have difficulty translating phrase "*exerted on*" into vector diagram form.

Coulomb's Law Quiz in Multiple Representations

IF YOU WANT A QUESTION GRADED OUT OF THREE POINTS (–1 [<u>MINUS ONE</u>] FOR WRONG ANSWER!!) WRITE "3" IN SPACE PROVIDED ON EACH QUESTION.

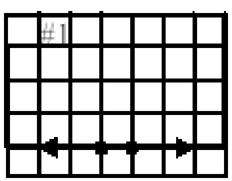
1. When two identical, isolated charges are separated by two centimeters, the magnitude of the force exerted by each charge on the other is eight newtons. If the charges are moved to a separation of eight centimeters, what will be the magnitude of that force now?

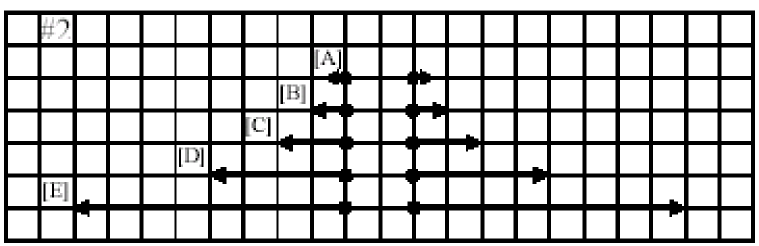
A. one-half of a newton
B. two newtons
C. eight newtons
D. thirty-two newtons
E. one hundred twenty-eight newtons

Grade out of three? Write "3" here: ______

verbal

2. Figure #1 shows two identical, isolated charges separated by a certain distance. The arrows indicate the forces exerted by each charge on the other. The same charges are shown in Figure #2. Which diagram in Figure #2 would be correct?





A.
B.
C.
D.
E.

Grade out of three? Write "3" here: ______

diagrammatic

3. Isolated charges q_1 and q_2 are separated by distance r, and each exerts force F on the other. $q_1^{initial} = q_1^{final}$ and $q_2^{initial} = q_2^{final}$; $r^{initial} = 10m$; $r^{final} = 2m$. $F^{initial} = 25N$; $F^{final} = ?$

A. 1 N
B. 5 N
C. 25 N
D. 125 N
E. 625 N

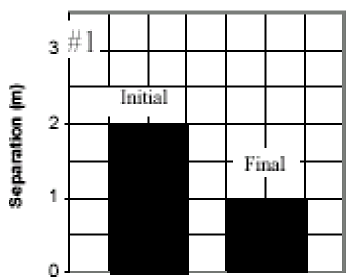
Grade out of three? Write "3" here: ______

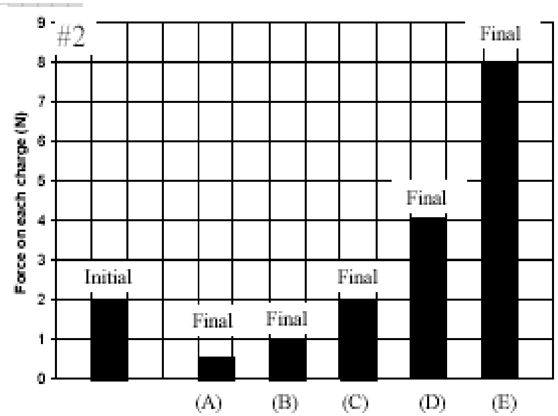
mathematical/symbolic

4. Graph #1 refers to the initial and final separation between two identical, isolated charges. Graph #2 refers to the initial and final forces exerted by each charge on the other. Which bar is correct?

Grade out of three? Write "3" here: ______

A.
B.
C.
D.
E.





graphical

Outline

- Overview of goals and methods of PER

Investigation of Students' Reasoning:

- Students' reasoning in thermodynamics
- Diverse representational modes in student learning

Curriculum Development:

- Instructional methods and curricular materials for large-enrollment physics classes

Assessment of Instruction:

- Measurement of learning gain
- Potential broader impact of PER on undergraduate education

Origins of Learning Difficulties

- Students hold many firm ideas about the physical world that may conflict strongly with physicists' views.
- Students need guidance in scientific reasoning employing abstract concepts.
- Most introductory students lack "active learning" skills that would permit more efficient mastery of physics concepts.

Success Hinges on "Active Learning"

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

    [*scrutinize implicit assumptions; pose their own questions; etc.]*
  - they have the confidence to confront areas of confusion

- 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 guidance by instructors, aided by appropriate curricular materials

Keystones of Innovative Pedagogy

- problem-solving activities during class time
- deliberately elicit and address common learning difficulties
- guide students to “figure things out for themselves” as much as possible

“Fully Interactive” Physics Lecture

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

- Very high levels of student-student and student-instructor interaction
- Simulate one-on-one dialogue of instructor’s office
- Use numerous structured question sequences, focused on specific concept: small conceptual “step size”
- Use student response system to obtain instantaneous responses from all students simultaneously (e.g., “flash cards”)

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

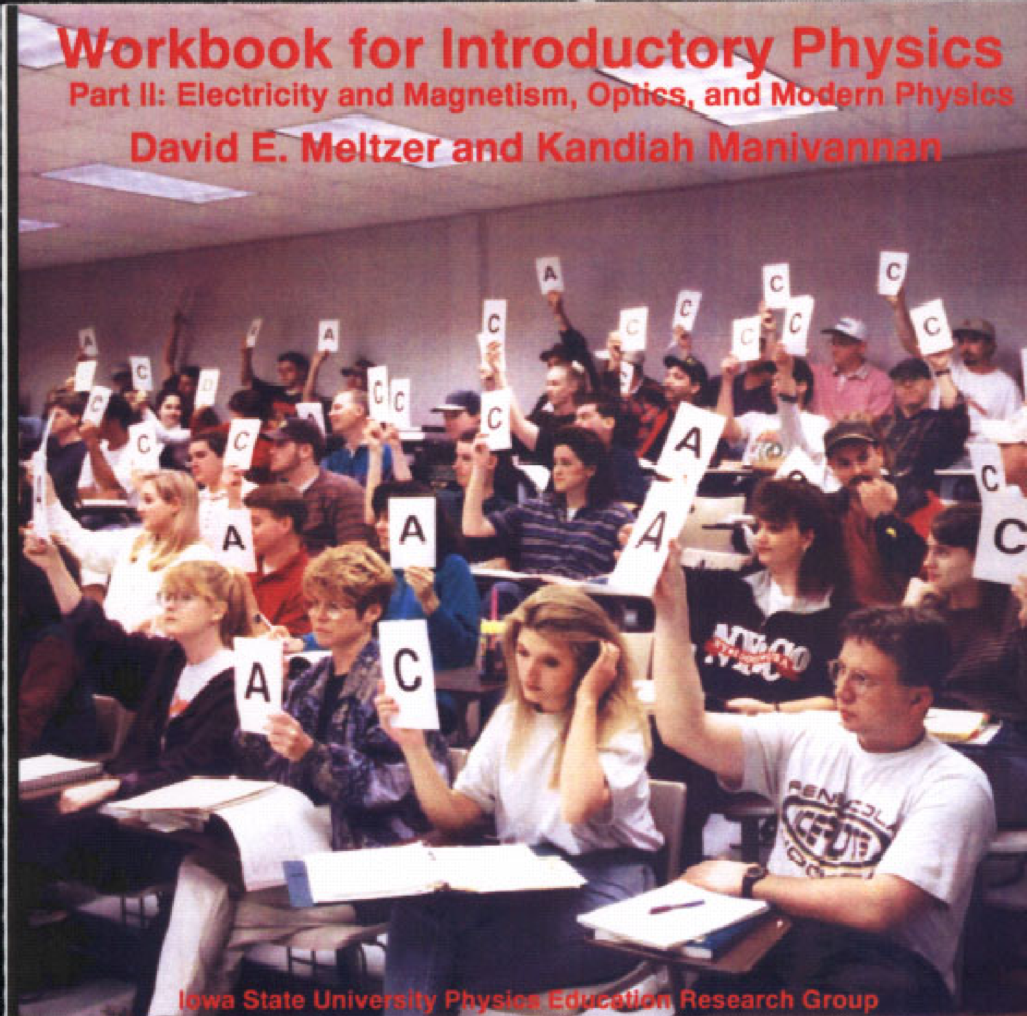
Workbook for Introductory Physics (DEM and K. Manivannan, CD-ROM, 2002)

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

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Part 2: In-Class Questions and Worksheets, Chapters 1-8

Part 3: Lecture Notes

Part 4: Additional Worksheets

Part 5: Quizzes

Part 6: Exams and Answers

Part 7: Additional Material

Part 8: "How-to" Articles

Part 9: Flash-Card Masters

Part 10: Video of Class video

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Curriculum Development on the Fast Track

- Need curricular materials for complete course $\Rightarrow$ must create, test, and revise "on the fly"
- Daily feedback through in-class use aids assessment
- Pre- and post-testing with standardized diagnostics helps monitor progress

Components of Workbook

- Multiple-choice “flash-card” questions
- Free-response worksheets
- Lecture Notes (text reference)
- Quizzes and Exams

Chapter 1 Electrical Forces

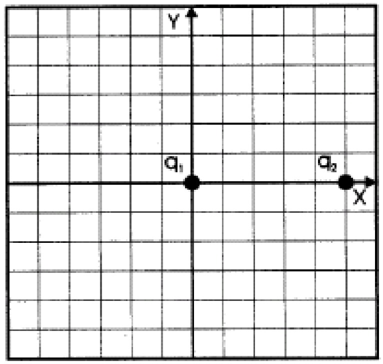
"Flash-Card" Questions

In-Class Questions

Prerequisite Concepts:

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

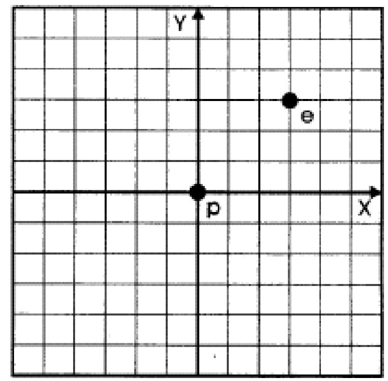
B. 

C. 

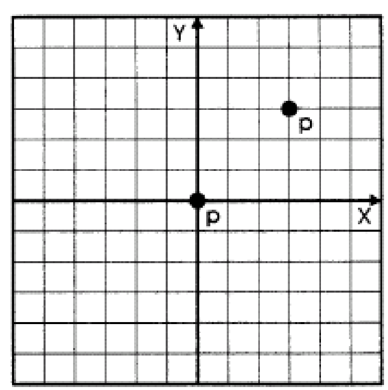
D. 

E. 

F. 



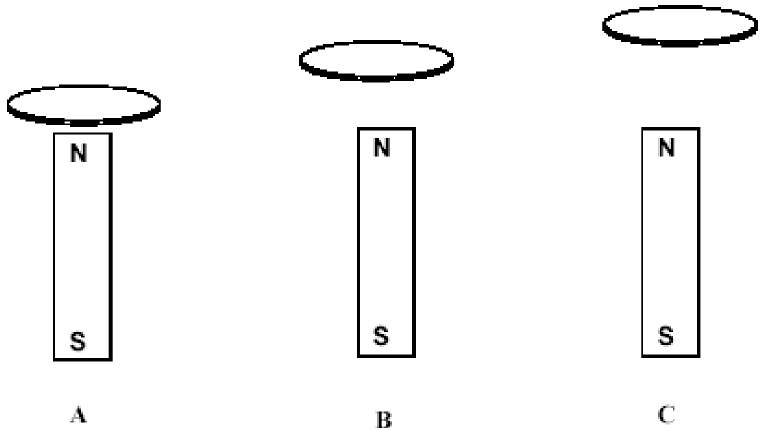
4. In this figure, a proton is located at the origin, and a proton is located at the point (3m, 3m). The vector representing the electrical force on the proton *at the origin* makes what angle with respect to the positive x axis?



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

Magnetic Induction Worksheet

1. In diagrams A, B, and C, three identical bar magnets and three identical wire loops are shown. ***All three loops remain fixed in the positions shown.***



Worksheets (free-response)

a) Is there any magnetic flux in:

Loop A? ________

Loop B? ________

Loop C? ________

b) Rank the magnitude of the magnetic flux in loops A, B, and C. If all three are zero, state that explicitly. Explain your answer.

c) Is there any current flowing in:

Loop A? ________

Loop B? ________

Loop C? ________

d) Rank the magnitude of the current flowing in loops A, B, and C. If all three currents are zero, state that explicitly. Explain your answer.

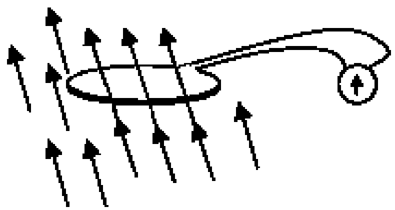
Chapter 10 Notes: Magnetic Induction

Lecture Notes

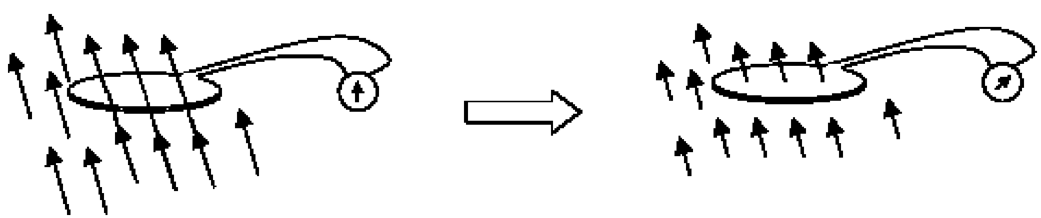
How can a changing magnetic field cause an electric current to flow?

Eleven years after the connection between magnetism and electricity was first reported by Oersted, the British scientist Michael Faraday made one of the most important discoveries in the history of physics. Oersted had found that an electric current could influence the motion of a compass needle; this showed that an electric current produced a magnetic field. Faraday found that, under certain specific circumstance, a magnet (such as a large compass needle) could itself *produce* an electric current (i.e., it could cause charges to begin to move). Although an electric current ***always*** produces a magnetic field, Faraday found that a magnet could only produce an electric current under one or more of three basic conditions: (1) the magnetic field varied in ***magnitude***; (2) the magnetic field varied in ***direction***; (3) the conducting path (which would carry the current) ***varied in shape***.

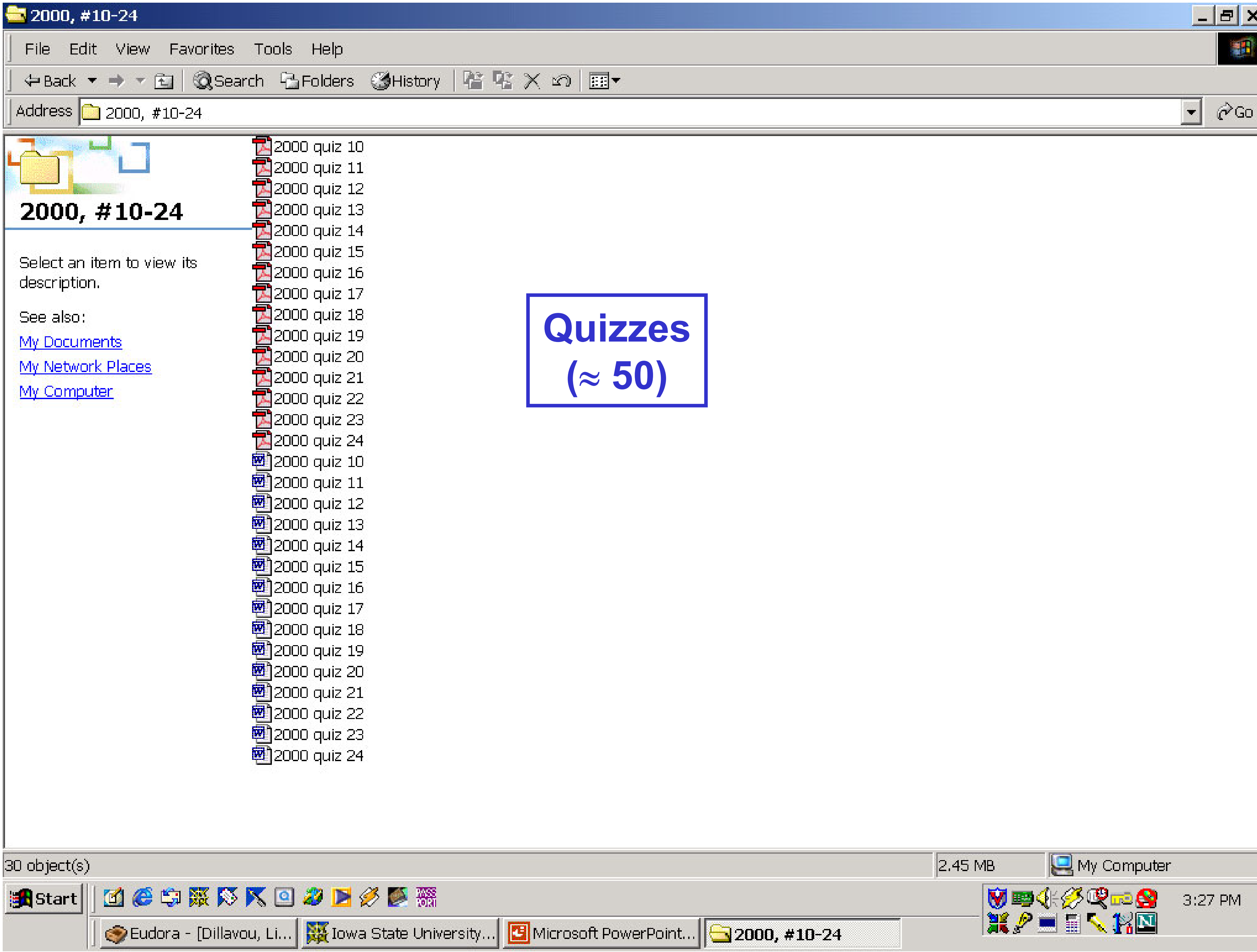
These situations can be illustrated by three different experiments, all involving a magnetic field and a closed loop of conducting material. We could connect a galvanometer (a current-detecting device) to the loop to determine whether or not a current is flowing. We could use a permanent magnet to produce the magnetic field, or instead use the uniform field inside a solenoid. In the diagram below, we have placed a conducting loop in a uniform magnetic field (indicted by the arrows); the loop is connected to a galvanometer. The needle of the galvanometer will deflect (move away from its initial position) if a current if produced in the loop. If the needle is in its initial position (as shown here), there is ***no*** current flowing in the loop.



In the ***initial*** situation shown above, where neither the loop nor the magnetic field is changing in any way, ***no current*** is observed to flow in the loop. However, if we ***change the magnitude*** of the magnetic field – either an increase or a decrease – then a current ***does*** flow in the loop, as shown here:



However, if the magnetic field magnitude ***stops changing***, the current will abruptly cease flowing and the galvanometer needle will go back to its initial position (again indicating "zero current"):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Select an item to view its description.
See also:
My Documents
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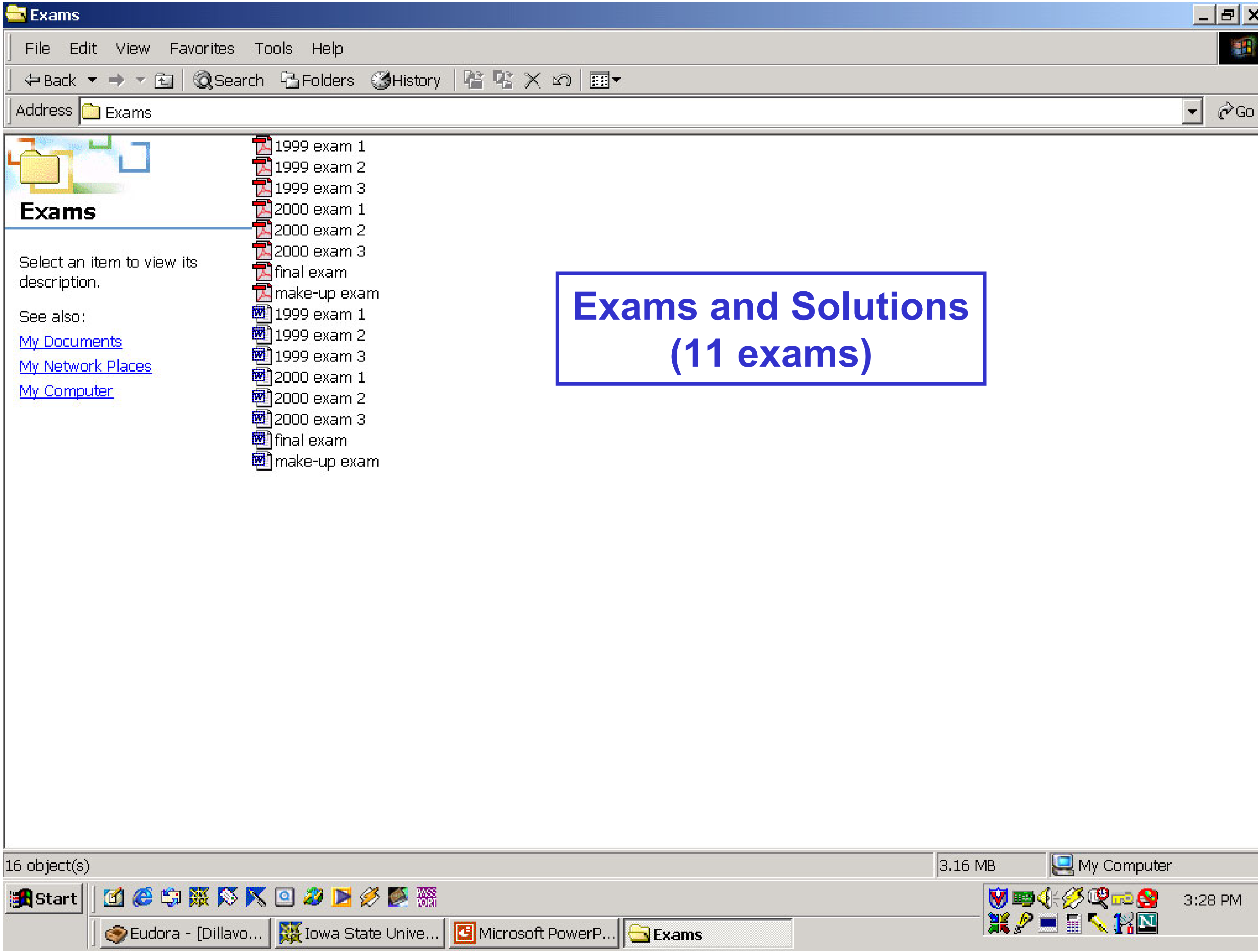

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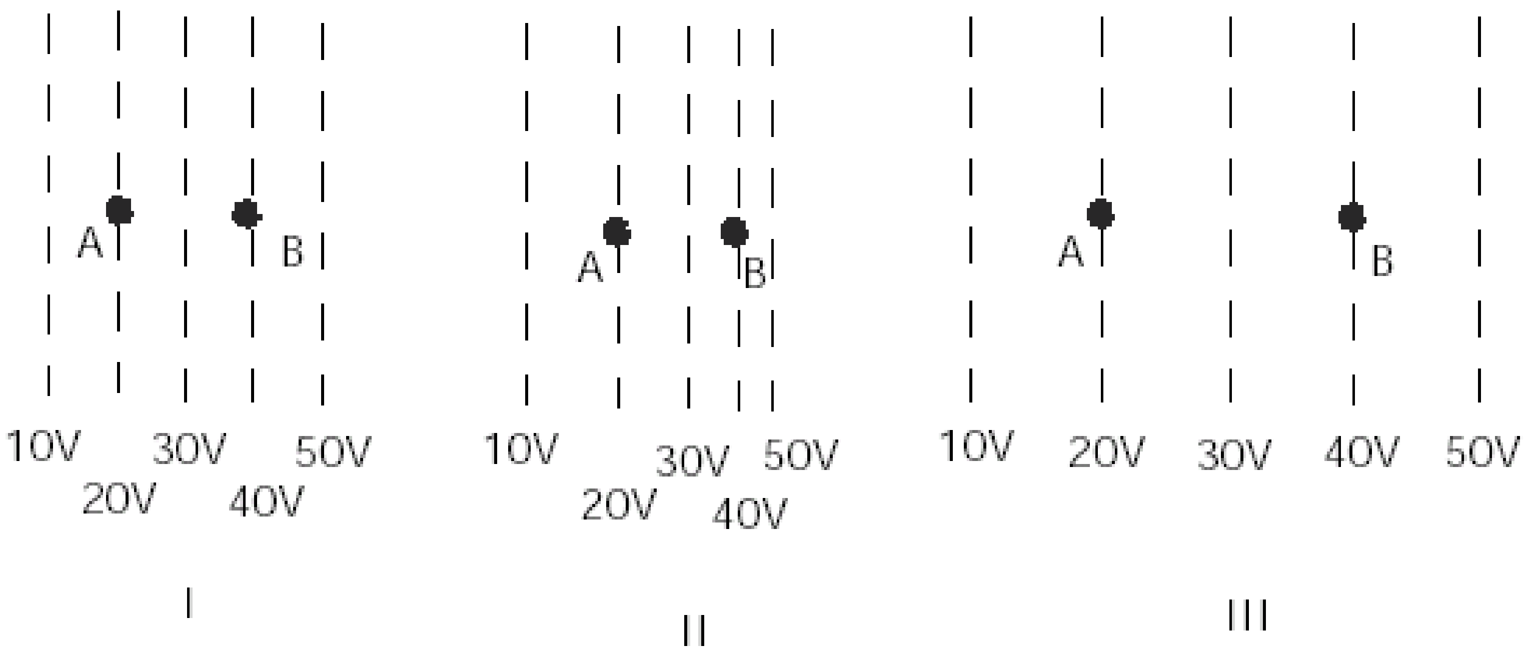
Assessment Data

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

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

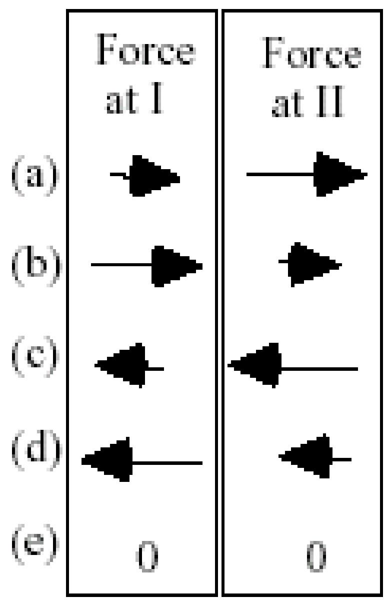
In the figures below, the dotted lines show the equipotential lines of electric fields. (A charge moving along a line of equal potential would have a constant electric potential energy.) A charged object is moved directly from point A to point B. The charge on the object is +1 μC.

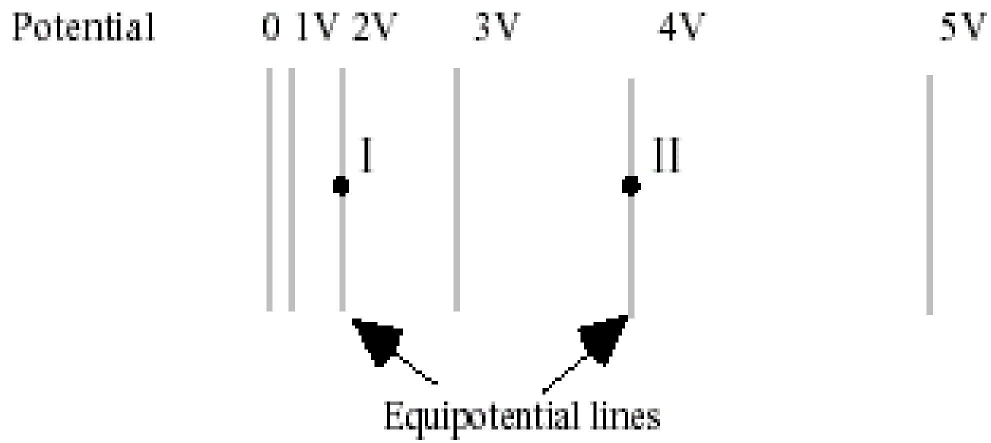


1. How does the magnitude of the electric field at B compare for these three cases?
   (a) I > III > II
   (b) I > II > III
   (c) III > I > II
   (d) II > I > III
   (e) I = II = III

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

2. A positively-charged proton is first placed at rest at position I and then later at position II in a region whose electric potential (voltage) is described by the equipotential lines. Which set of arrows on the left below best describes the relative magnitudes and directions of the electric force exerted on the proton when at position I or II?





Assessment Data

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

Sample	*N*	Mean pre-test score	Mean post-test score	<g>
National sample (algebra-based)	402	**27%**	**43%**	**0.22**
National sample (calculus-based)	1496	**37%**	**51%**	**0.22**
ISU 1998	70	**30%**	**75%**	**0.64**
ISU 1999	87	**26%**	**79%**	**0.71**
ISU 2000	66	**29%**	**79%**	**0.70**

Outline

- Overview of goals and methods of PER

Investigation of Students' Reasoning:

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Measures of Learning Gain

- Single exam measures only instantaneous knowledge state, but instructors are interested in improving *learning*, i.e., transitions between states.

- Need a measure of learning gain that has maximum dependence on *instruction*, and minimum dependence on students' *pre-instruction* state.

$\Rightarrow$ *search for measure that is correlated with instructional activities, but has minimum correlation with pretest scores.*

Normalized Learning Gain “*g*”

R. R. Hake, Am. J. Phys. ***66****, 64 (1998)*

$$g \equiv \frac{posttest\ \ score - pretest\ \ score}{maximum\ \ possible\ \ score - pretest\ \ score} = \frac{gain}{maximum\ \ possible\ \ gain}$$

In a study of 62 mechanics courses enrolling over 6500 students, Hake found that mean normalized gain <*g*> on the Force Concept Inventory is:

- **virtually independent of class mean pretest score (*r* = +0.02);**
- **= 0.23±0.04(s.d.) for traditional instruction, nearly independent of instructor;**
- **=0.48±0.14(s.d.) for courses employing “interactive engagement” active-learning instruction.**

These findings have been largely confirmed in hundreds of physics courses worldwide

But is *g* really independent of pre-instruction state?

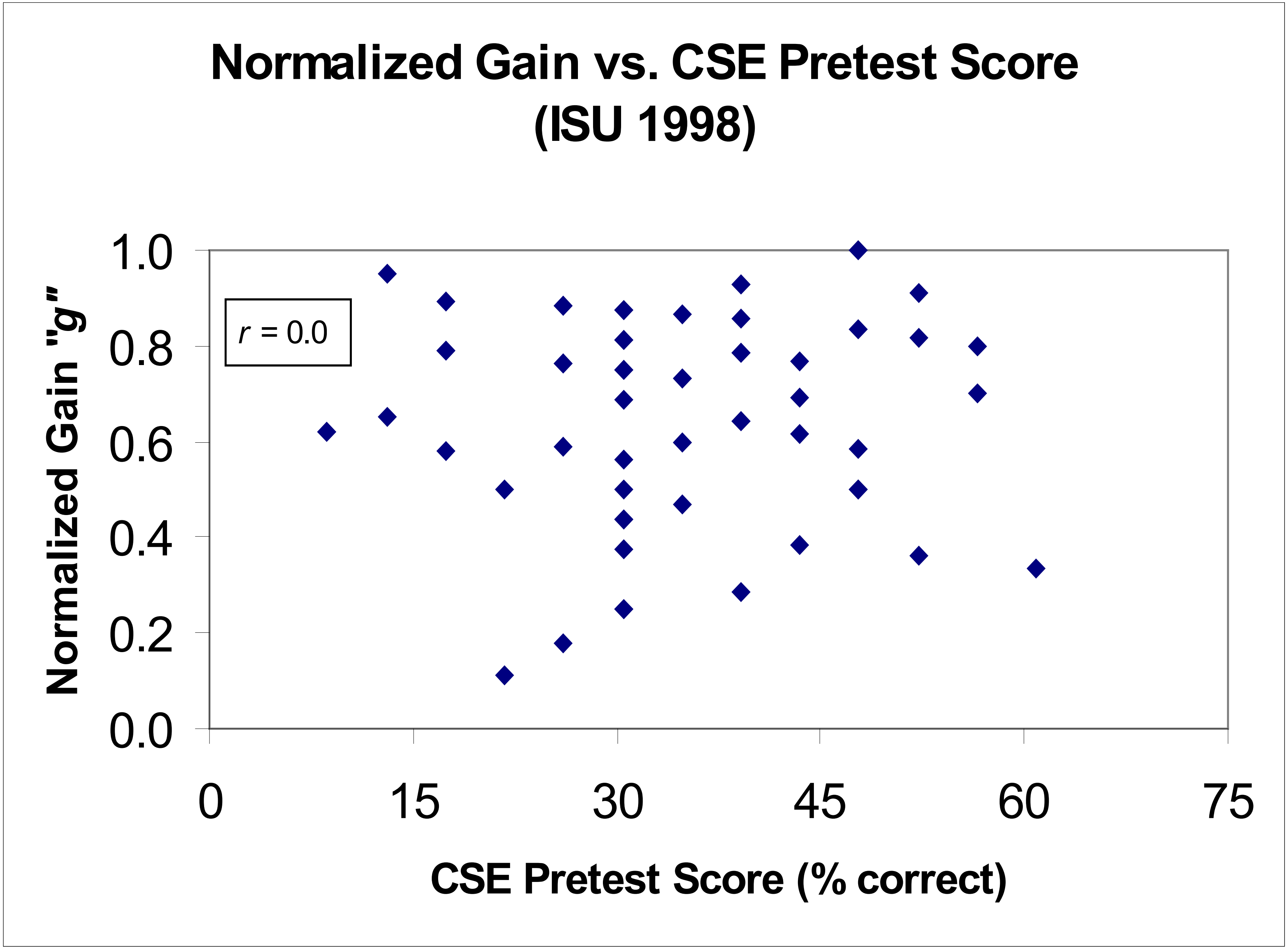
Possible "hidden variables" in students' pre-instruction mental state:

- mathematical skill *R. Hake et al., 1994; M. Thoresen and C. Gross, 2000; DEM, PERS of AJP (in press)*
- spatial visualization ability *R. Hake 2002*
- gender *L. McCullough 2000; L. McCullough and DEM, Proc. of PER Conf. 2001, R. Hake 2002*
- reasoning ability *J. M. Clement, 2002*

Relationship between Mathematical Ability and Learning Gains in Physics

DEM, Am. J. Phys. ***70****, 1259 (2002)*

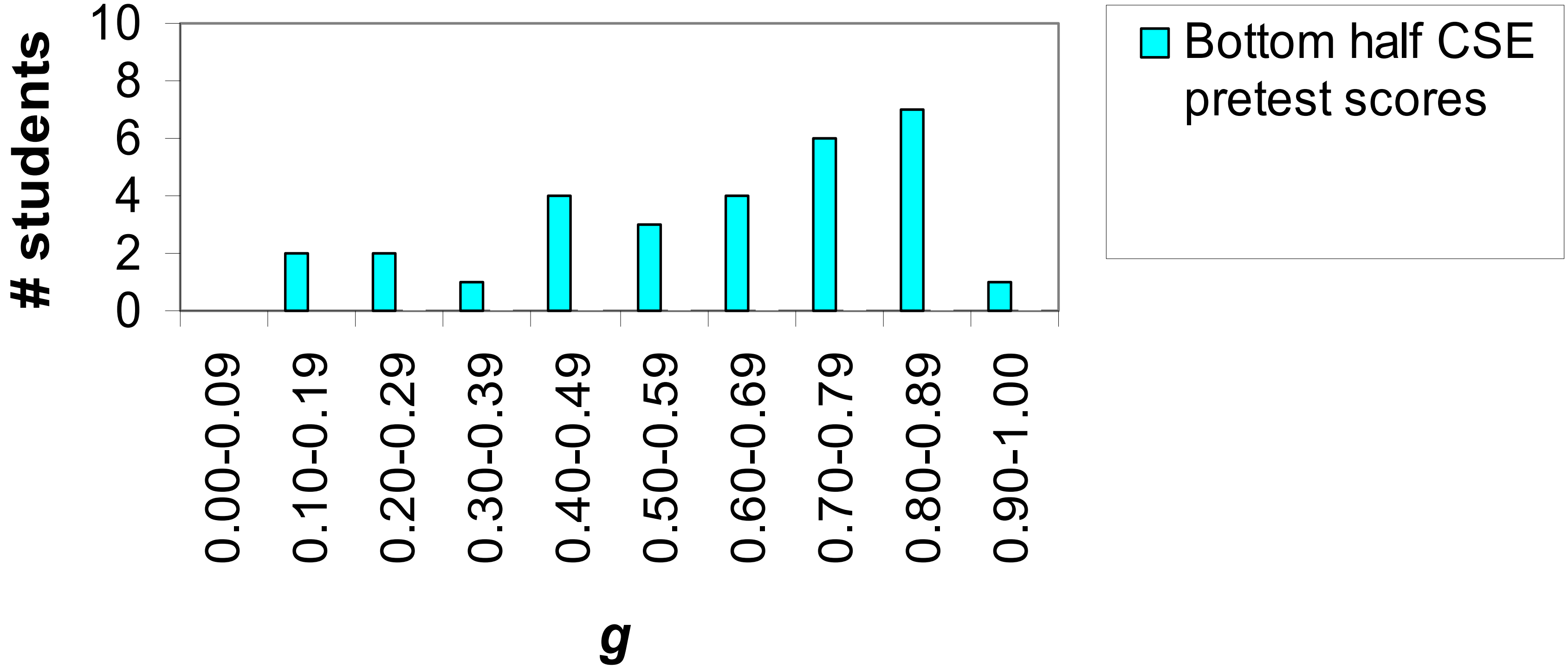
- Investigation of four separate introductory E & M courses (algebra-based, second semester)
- No correlation between individual students' normalized learning gain *g* and their pre-instruction score on physics concept test *(Conceptual Survey of Electricity, "CSE")*



Normalized Gain vs. CSE Pretest Score
(ISU 1998)
r = 0.0
Normalized Gain "g"
1.0
0.8
0.6
0.4
0.2
0.0
0
15
30
45
60
75
CSE Pretest Score (% correct)

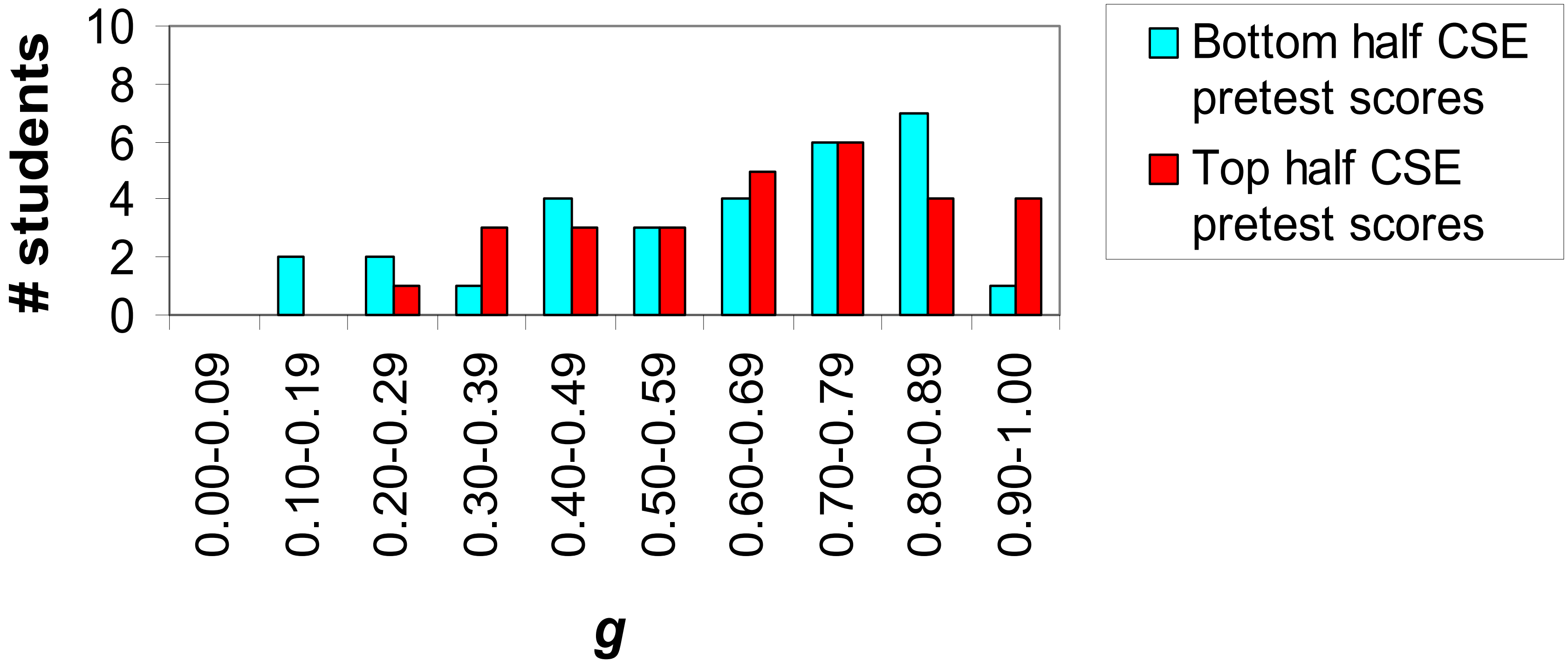
Distribution of Gains: ISU 1998

(high and low CSE pretest scores)



Distribution of Gains: ISU 1998

(high and low CSE pretest scores)



Relationship between Mathematical Ability and Learning Gains in Physics

DEM, Am. J. Phys. ***70****, 1259 (2002)*

- Investigation of four separate introductory E & M courses (algebra-based, second semester)
- No correlation between individual students' normalized learning gain *g* and their pre-instruction score on physics concept test *(Conceptual Survey of Electricity, "CSE")*
- Significant correlation (r = +0.30 – +0.46) between individual students' *g* and their pre-instruction score on algebra/trigonometry skills test *(ACT Math Test and ISU Math Diagnostic)*

DIAGNOSTIC TEST

1. What is the value of x in the expression

$$x = p(p + q) + 4$$

if $p = -2$ and $q = 5$?

a. -2 b. -3 c. 4 d. -6 e. 18

2. Given $x + 2 = 2(x - 3)$, what is the value of x?

a. 2 b. 3 c. 4 d. 6 e. 8

3. $\sqrt{15^2 - 9^2} =$ ________.

a. 6 b. $\sqrt{6}$ c. 12 d. $\sqrt{12}$ e. $\sqrt{135}$

4. Express a speed of 30 kilometers per hour in meters/second.

a. 108,000 b. 0.008 c. 0.03 d. 3.0 e. 8.3

5. What is the value of x in the following equations?

$$x + 4t = 2$$
$$2x - 2 = t + 2$$

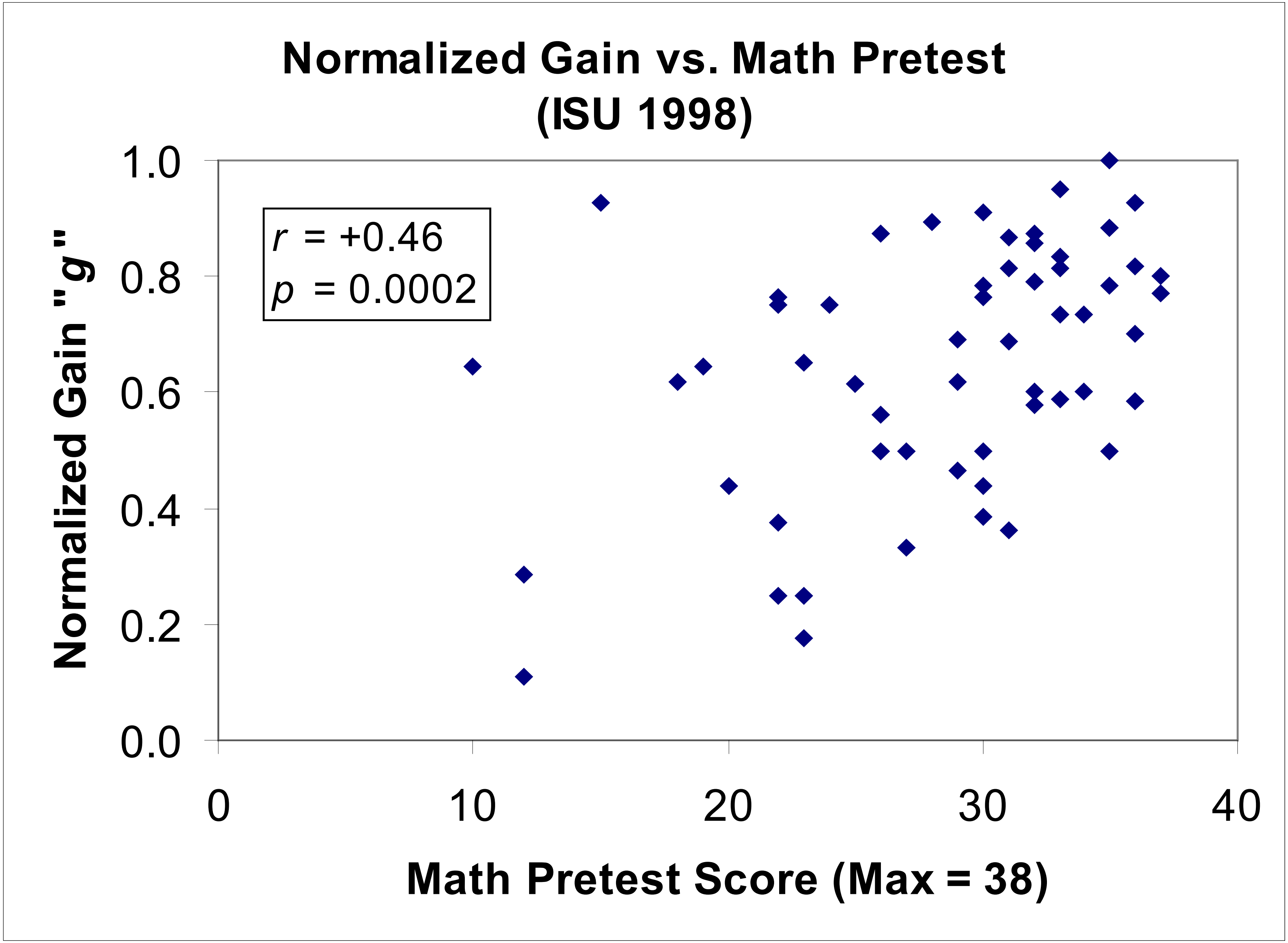
a. -2/9 b. 2 c. 1/2 d. 4 e. 1/4

6. Find y as a function of x from the following equations.

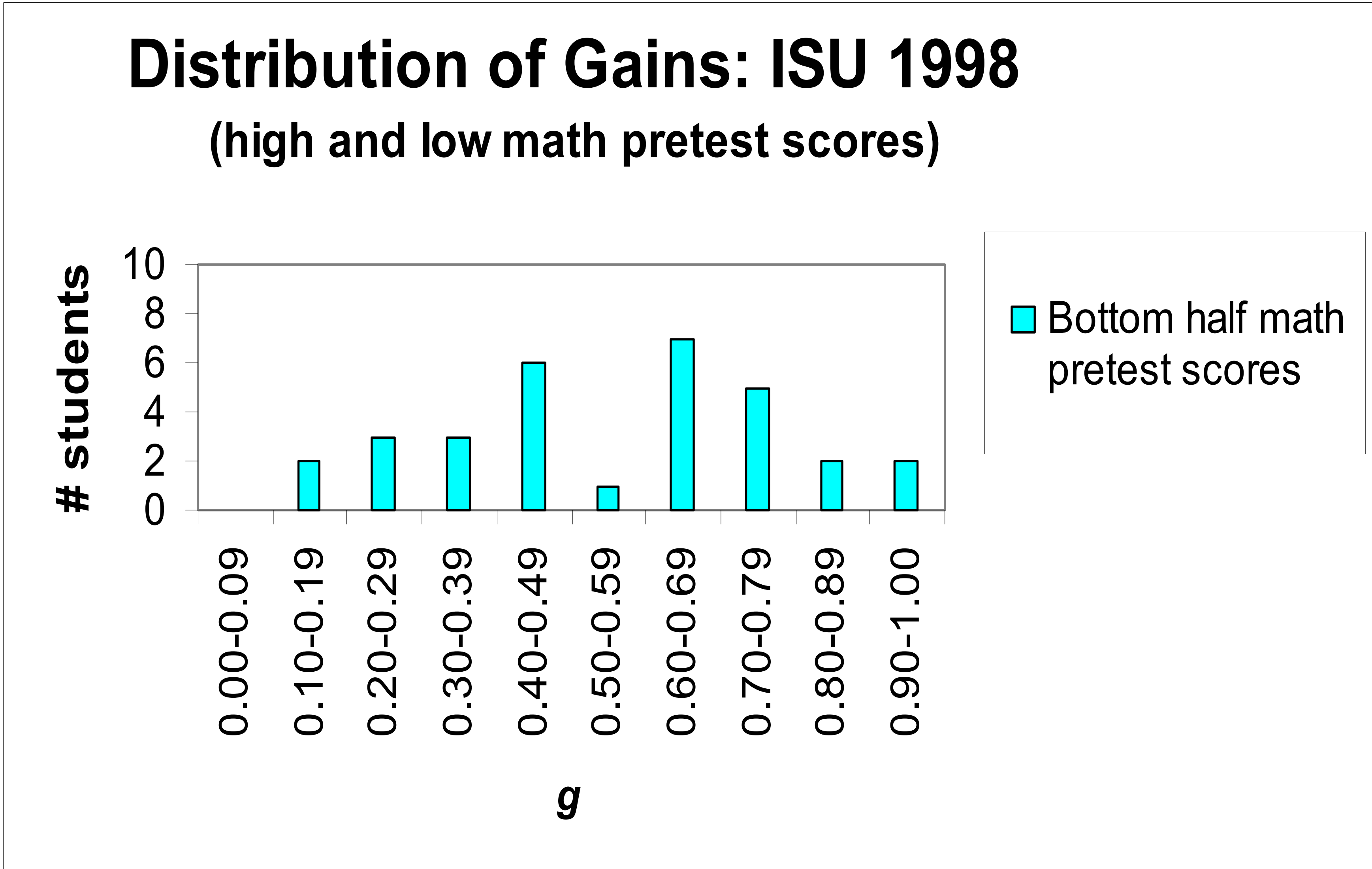
$$2x - t = 2$$
$$y - 4 = 3t$$

a. $y = 3x + 4$ b. $y = 10 - 3x$ c. $y = 3x + 6$

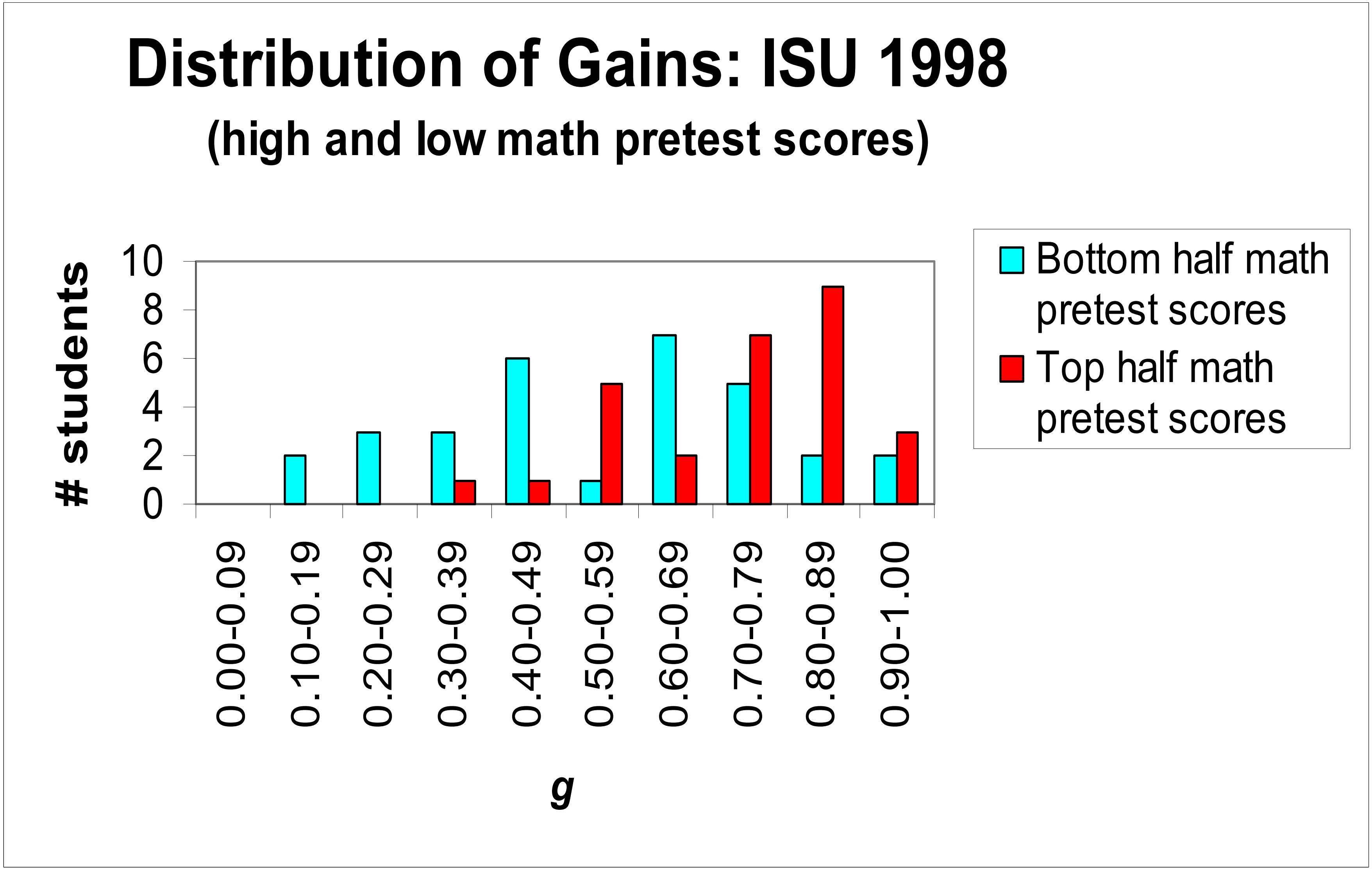
d. $y = 4 - 6x$ e. $y = 6x - 2$



Normalized Gain vs. Math Pretest
(ISU 1998)
r = +0.46
p = 0.0002
Normalized Gain "g"
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
Math Pretest Score (Max = 38)



Distribution of Gains: ISU 1998
(high and low math pretest scores)
students
10
8
6
4
2
0
0.00-0.09
0.10-0.19
0.20-0.29
0.30-0.39
0.40-0.49
0.50-0.59
0.60-0.69
0.70-0.79
0.80-0.89
0.90-1.00
g
Bottom half math pretest scores


Distribution of Gains: ISU 1998
(high and low math pretest scores)
students
10
8
6
4
2
0
0.00-0.09
0.10-0.19
0.20-0.29
0.30-0.39
0.40-0.49
0.50-0.59
0.60-0.69
0.70-0.79
0.80-0.89
0.90-1.00
g
Bottom half math pretest scores
Top half math pretest scores

Second-Order Effects on *g*

- Normalized gain *g* not correlated with pre-instruction ***physics*** knowledge
- Normalized gain *g* ***is*** correlated with pre-instruction math skill
- When comparing *g* for diverse student populations, may need to take into account students' pre-instruction state

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How Can PER be a Model for Improving Undergraduate Education?

Physicists bring a powerful set of tools to the task of analyzing and improving learning of their subject:

- Precision in definitions: operational definitions based on measurement procedures
- Search for fundamental determining factors
- Stress on identification and control of variables
- Familiarity with complex relationships *(not everything is linear!)*
- Controlling approximations through careful estimation

Achievements of PER as a Field

- Sustained and systematic investigation of students' reasoning has yielded reliable and reproducible results.
- Research-based curriculum and instruction has documented learning improvements in specific areas.
- Growth and development of PER community is evidence for long-term viability of discipline-based educational research at the university level.

Summary

- Investigation of students' reasoning lays the basis for improved curriculum

  e.g. curricular materials in thermodynamics

- Probing deep-seated learning issues can lead toward more precise targeting of instruction

  e.g., understanding students' difficulties with diverse representations

- Continual process of development and assessment of research-based curriculum holds promise for sustained improvements in learning.