The Questions We Ask and Why: Methodological Orientation in Physics Education Research

David E. Meltzer

Department of Physics and Astronomy

Iowa State University

Supported in part by NSF Grants DUE-9981140, REC-0206683, and DUE-0243258

Outline

- Objectives of the Endeavor
- A Model for Students' Knowledge
- Probing Students' Knowledge
- Applying the Model: Thermodynamics research project
- Learning Difficulties, Not Alternative Theories
- How do we know our analysis is correct?
- Summary

Outline

- Objectives of the Endeavor
- A Model for Students' Knowledge
- Probing Students' Knowledge
- Applying the Model: Thermodynamics research project
- Learning Difficulties, Not Alternative Theories
- How do we know our analysis is correct?
- Summary

Objectives of the Endeavor: PER as an Applied Field

Goals for my research:

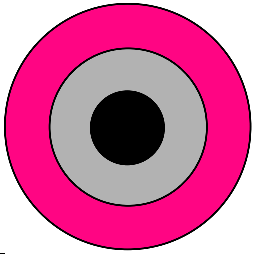
- Find ways to help students learn physics more effectively and efficiently
  - Develop deeper understanding of concepts
  - Appreciate overall structure of physical theory
- Help students develop improved problem-solving and reasoning abilities applicable in diverse contexts

Outline

- Objectives of the Endeavor
- A Model for Students' Knowledge
- Probing Students' Knowledge
- Applying the Model: Thermodynamics research project
- Learning Difficulties, Not Alternative Theories
- How do we know our analysis is correct?
- Summary

A Model for Students' Knowledge Structure

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



Archery Target: three concentric rings

- Central black bull's-eye: what students know well
  - *tightly linked network of well-understood concepts*
- Middle "gray" ring: students' partial and imperfect knowledge [Vygotsky: "Zone of Proximal Development"]
  - *knowledge in development: some concepts and links strong, others weak*
- Outer "white" region: what students don't know at all
  - *disconnected fragments of poorly understood concepts, terms and equations*

Response Characteristics Corresponding to Knowledge Structure

- When questions are posed related to black-region knowledge, students answer rapidly, confidently, and correctly – independent of context
- Questions related to gray region yield correct answers in some contexts and not in others; explanations may be incomplete or partially flawed
- Questions related to white region yield mostly noise: highly context-dependent, inconsistent, and unreliable responses, deeply flawed or totally incorrect explanations.

Teaching Effectiveness, Region by Region

- In central black region, difficult to make significant relative gains: instead, polish and refine a well-established body of knowledge
- Learning gains in white region minor, infrequent, and poorly retained: lack anchor to regions containing well-understood ideas
- 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.

Outline

- Objectives of the Endeavor
- A Model for Students' Knowledge
- Probing Students' Knowledge
- Applying the Model: Thermodynamics research project
- Learning Difficulties, Not Alternative Theories
- How do we know our analysis is correct?
- Summary

Probing Students’ Knowledge: Goals and Outcomes

- Probes of black-region knowledge yield consistent, reliable, and predictable results: not very interesting for research or teaching
- Probes of white region generate highly inconsistent, unreliable, context-dependent responses – also not very interesting.
- Probes of gray region often yield rich, diverse, and potentially useful data.

Characteristic Structure in Gray Region

- Mostly occupied by partially understood ideas with weak, broken, or miswired links to each other
- Some relatively stable, internally consistent conceptual "islands"
  - some correspond to reality, some do not
  - weakly linked to central bull's-eye region
  - loosely connected to each other (if at all)

[Somewhat analogous to Bao and Redish model]

Research Objectives: Determining Student’s “Response Function”

- attempt to map a student’s knowledge structure in gray region
- ascertain solidity of links, fluidity of thought, responsiveness to minimal guidance
- amalgamate set of individual mappings into an ensemble average representative of a specific sub-population
- determine intrinsic “linewidth” *(Redish, 1994),* i.e., range and distribution of mental patterns within target population

Outline

- Objectives of the Endeavor
- A Model for Students' Knowledge
- Probing Students' Knowledge
- Applying the Model: Thermodynamics research project
- Learning Difficulties, Not Alternative Theories
- How do we know our analysis is correct?
- Summary

Applying the Model: Design of a Research Project

- Research base required for curriculum development project in thermodynamics (NSF CCLI project with T. J. 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).

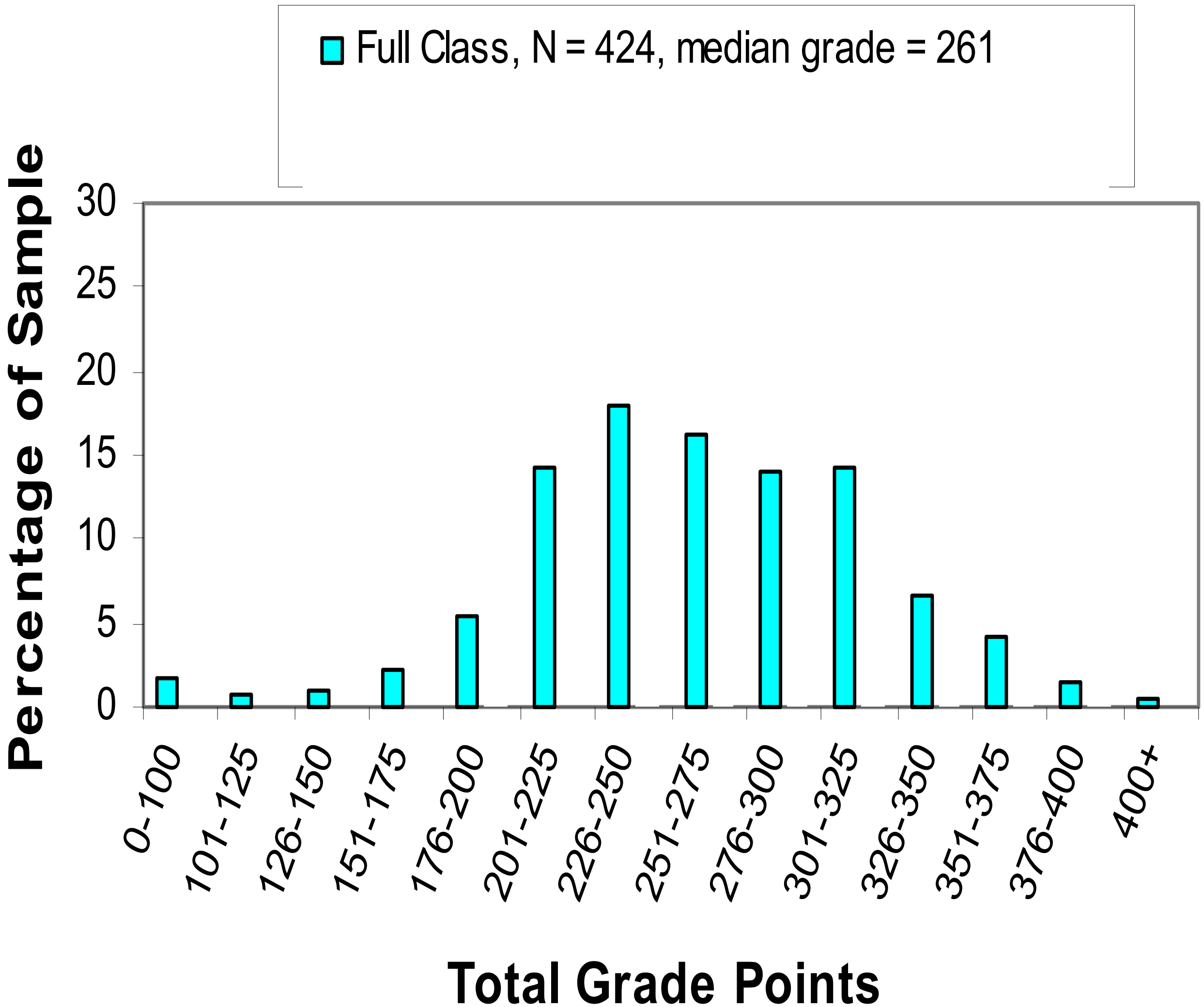
Applying the Model: Design of a Research Project

- Initial phases of research *(Meltzer, 2001)* and work by others had demonstrated that thermodynamics represented a “gray region” for this population *(Loverude, Kautz, and Heron, AJP 2002; etc.)*
- Interviews required to add depth to picture of students’ reasoning suggested by written diagnostics

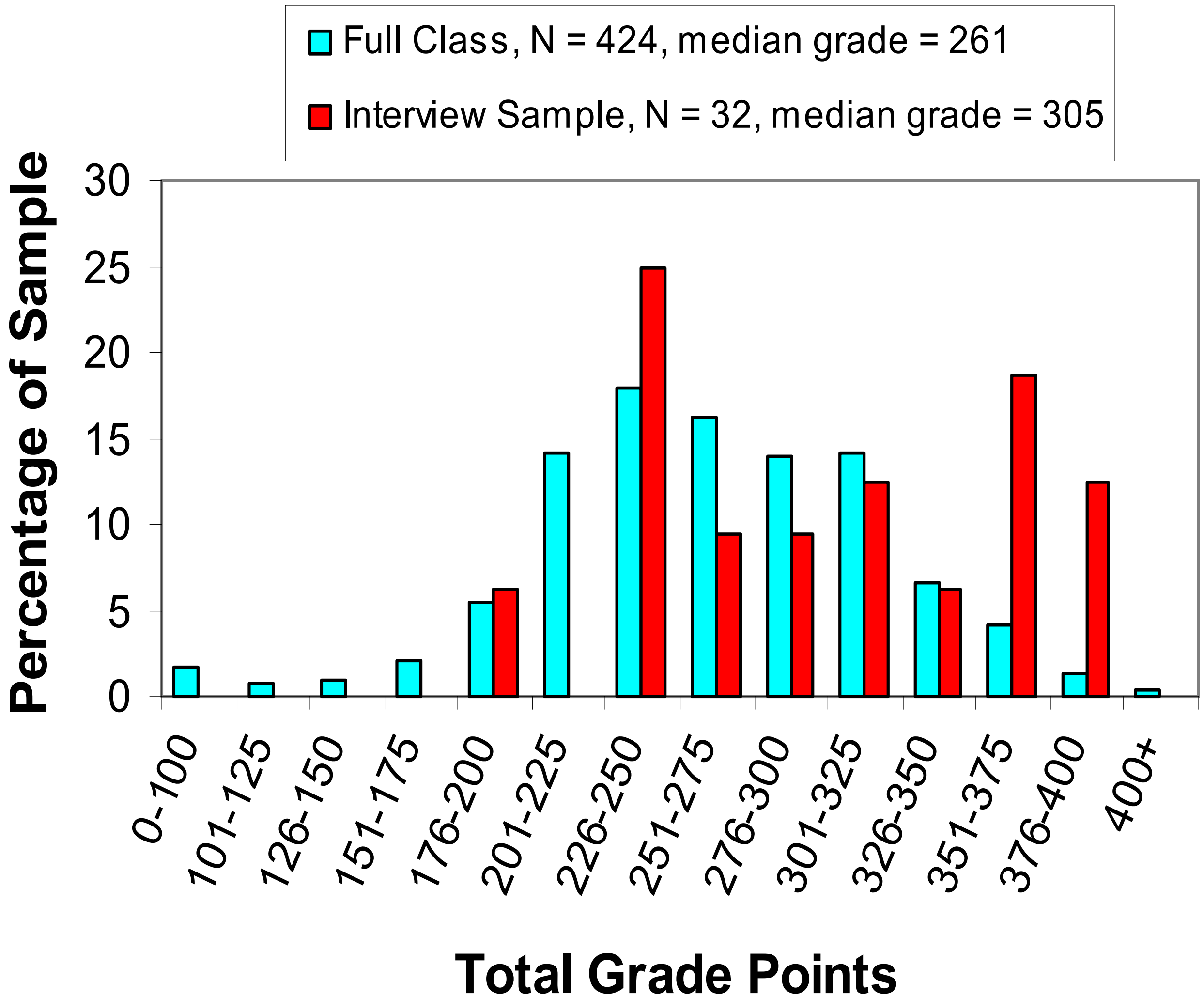
Applying the Model: Design of a Research Project

- Detailed interviews (avg. duration $\geq$ one hour) carried out with 32 volunteers during 2002 (total class enrollment: 424).
  - interviews carried out after all thermodynamics instruction had been completed
  - grades of interview sample far above class average

Grade Distributions: Interview Sample vs. Full Class



Grade Distributions: Interview Sample vs. Full Class



***Interview Sample*:**

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

Objectives of Interview Phase

- present students with ***real-world context*** (without real equipment!)
  - *goal of physics learning is to understand real-world phenomena*
- pose some fundamental ***baseline questions***
  - *constrain picture of students' thinking with lower bound*
- use different stages of cyclic process to present ***diverse contexts***
  - *need variety of contexts to probe depth of understanding*
- focus on ***learning difficulties*** (in context), gauge their prevalence
  - *understanding cause of difficulty is key tool for improving learning*
- gauge resilience and ***stability*** of students' concepts
  - *gauge intensity of difficulty to develop instructional strategy*

Alternative Objectives (Not a Focus of this Investigation)

- How students had acquired their knowledge
  - *I already knew they had numerous intersecting sources; no primary interest in unraveling previous learning process*
- Students learning styles and attitudes toward learning
  - *I already knew these left a lot to be desired, and that I would attempt to influence them with active-learning instructional methods*

Limitations on completeness of picture of students' thinking . . .

Alternative Objectives
(Not a Focus of this Investigation)

- How students had acquired their knowledge
  - *I already knew they had numerous intersecting sources; no primary interest in unraveling previous learning process*
- Students learning styles and attitudes toward learning
  - *I already knew these left a lot to be desired, and that I would attempt to influence them with active-learning instructional methods*

But any investigation is constrained in some fashion.

Surprises and Adjustments

- Large proportion (30-50%) of students unable to answer very fundamental questions regarding definitions of work and temperature
- Majority had strong belief in zero net work and heat transfer during cyclic process

➢ *Focused time and attention on key problem areas*

➢ *Guided students to provide additional details*

➢ *Adopted somewhat more leisurely pace*

Outline

- Objectives of the Endeavor
- A Model for Students' Knowledge
- Probing Students' Knowledge
- Applying the Model: Thermodynamics research project
- Learning Difficulties, Not Alternative Theories
- How do we know our analysis is correct?
- Summary

Learning Difficulties – Not Alternative Theories

- Even alternative conceptions expressed clearly and confidently are not likely to be used and defended with strength of full-blown “theory”
- Different contexts or representations may trigger links to better understood concepts and influence students to reconsider their reasoning.

Learning Difficulties – Not Alternative Theories: An Example

During interviews, lengthy description of cyclic process was given . . .

Interview Questions

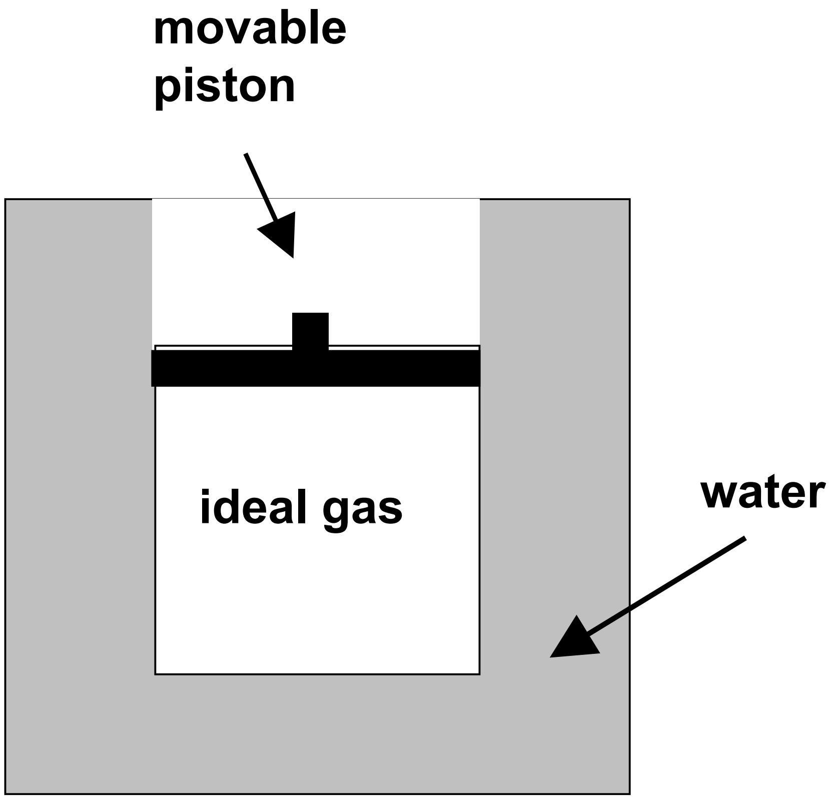
A fixed quantity of ideal gas is contained within a metal cylinder that is sealed with a movable, frictionless, insulating piston.

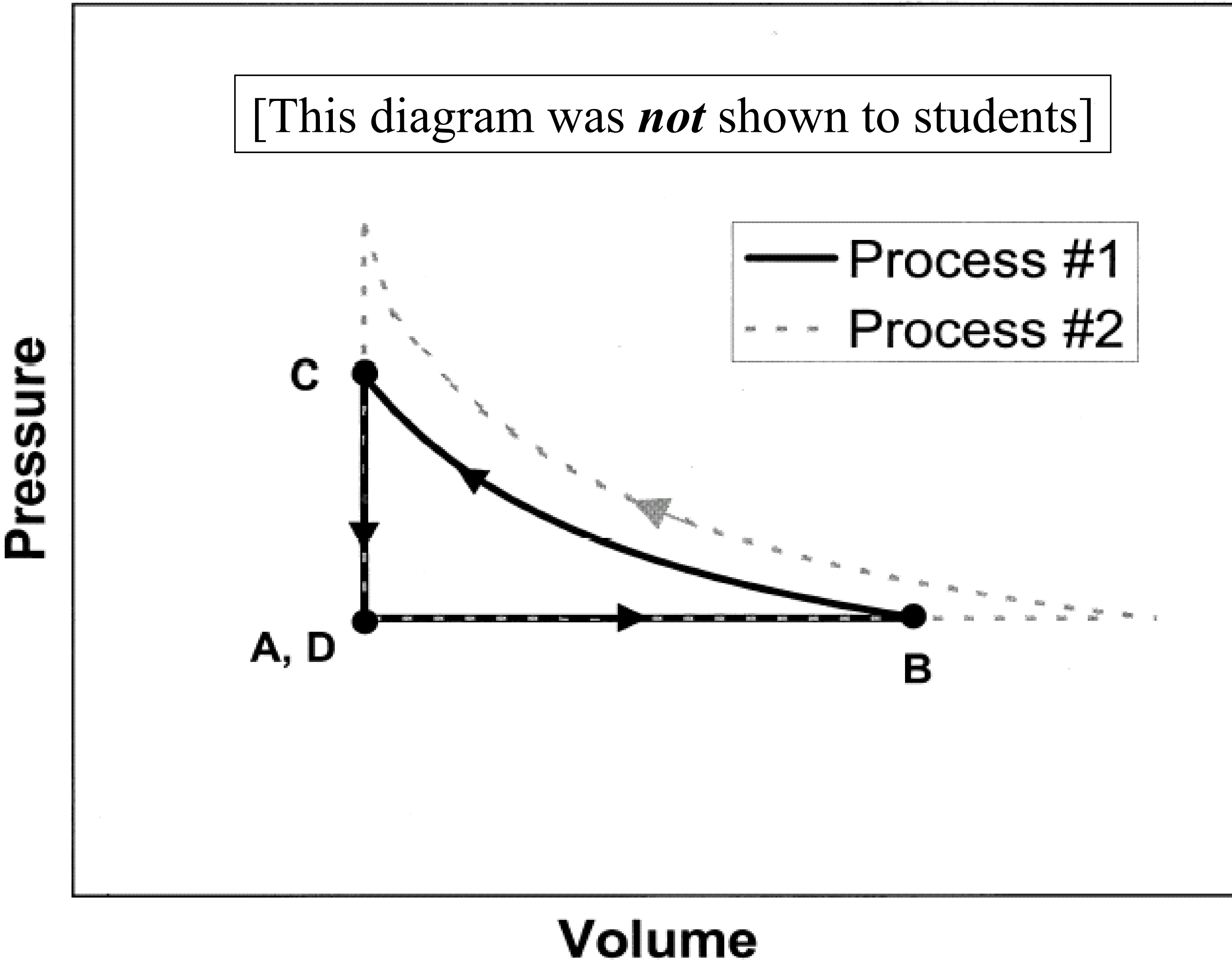
The cylinder is surrounded by a large container of water with high walls as shown. We are going to describe two separate processes, Process #1 and Process #2.

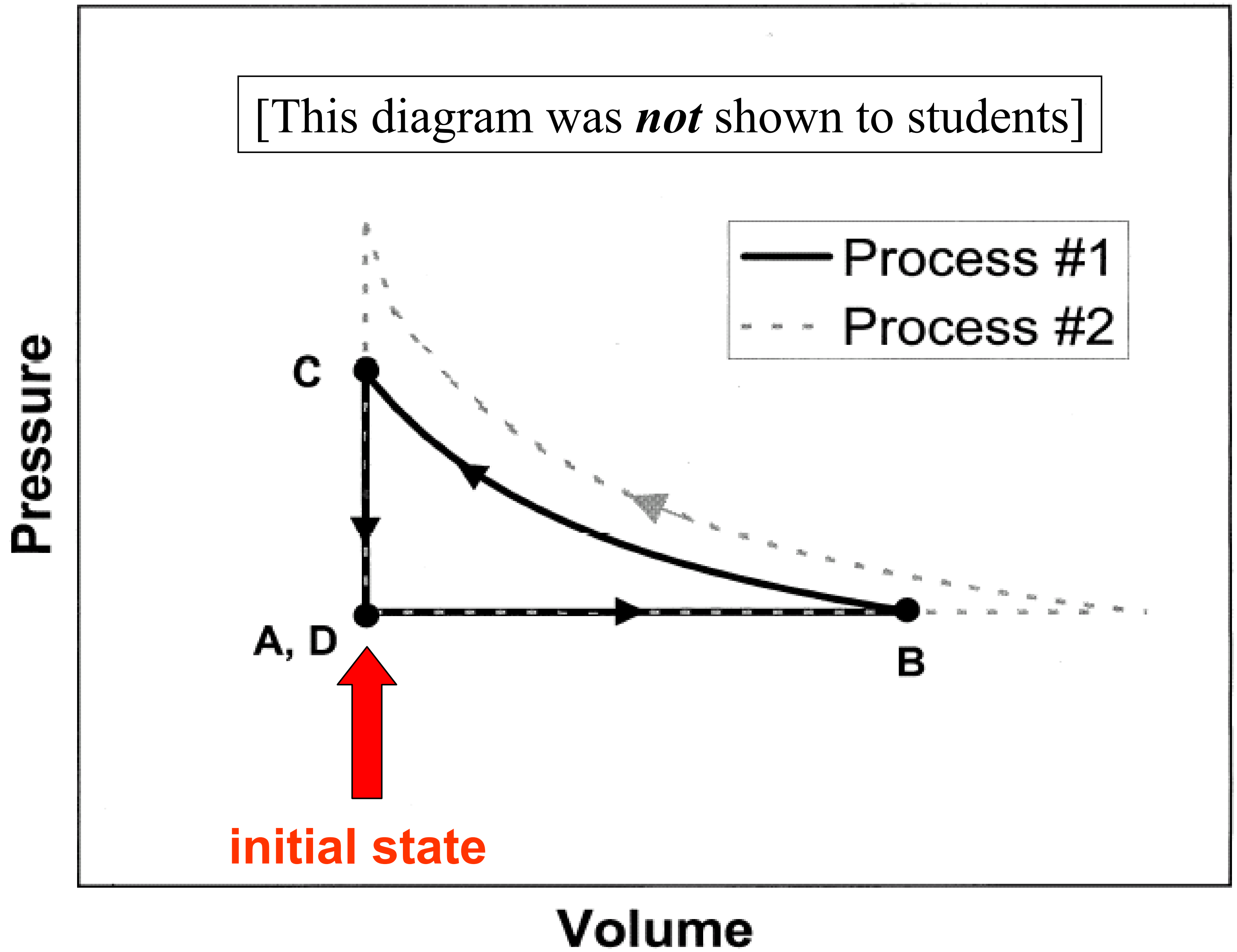
At initial time *A*, the gas, cylinder, and water have all been sitting in a room for a long period of time, and all of them are at room temperature

Time *A*

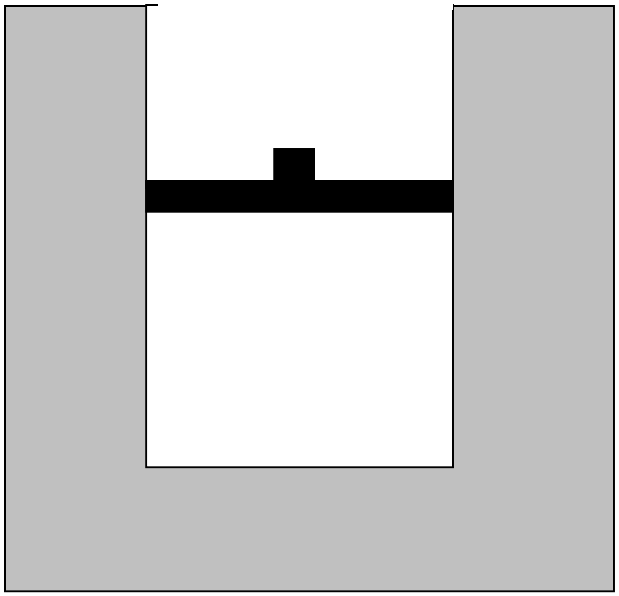
Entire system at room temperature.




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


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

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:

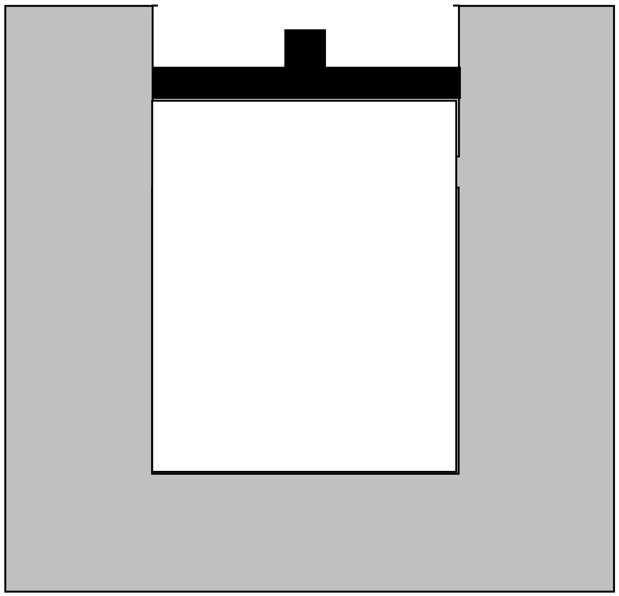


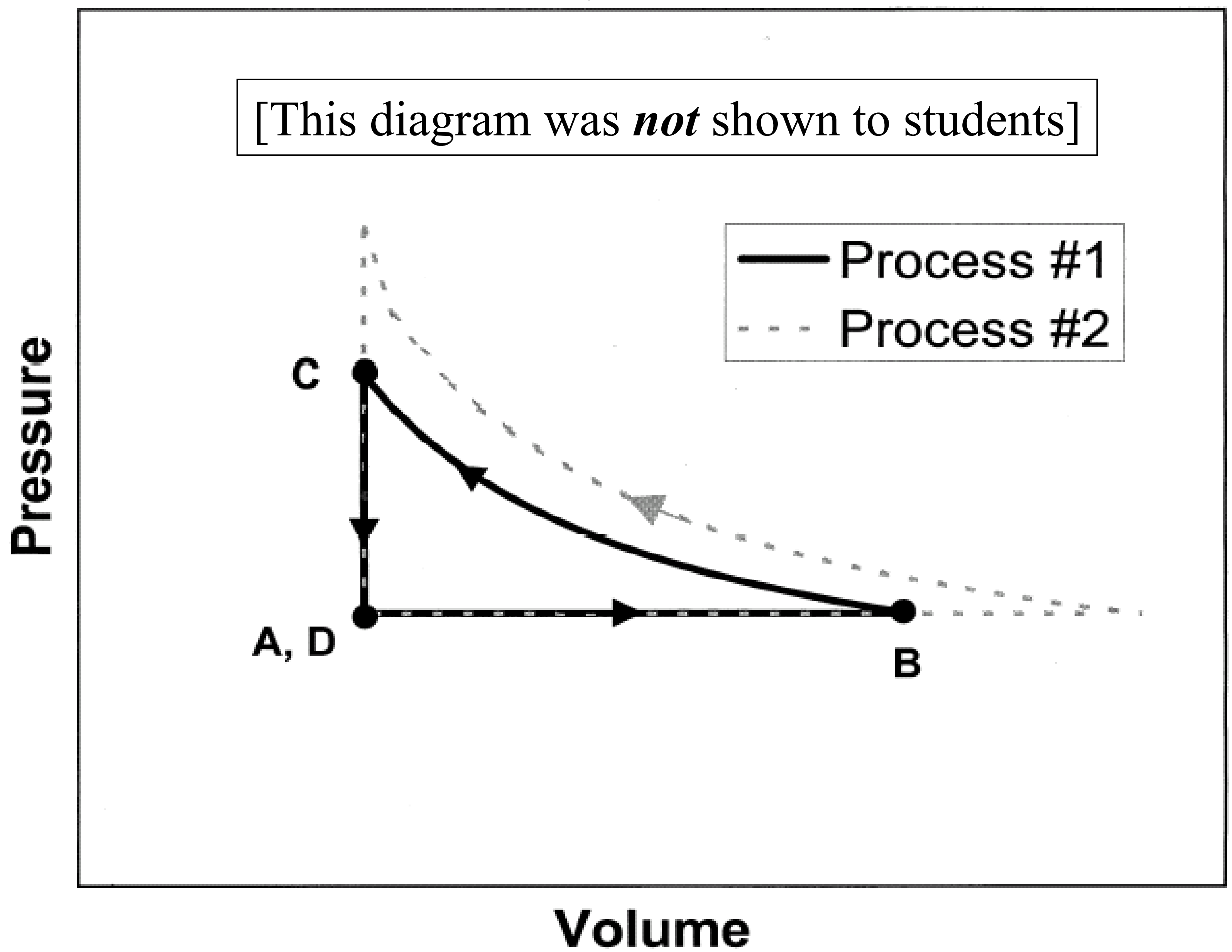
Step 1. We now begin Process #1: The water container is gradually heated, and the piston *very slowly* moves upward. At time *B* the heating of the water stops, and the piston stops moving when it is in the position shown in the diagram below:

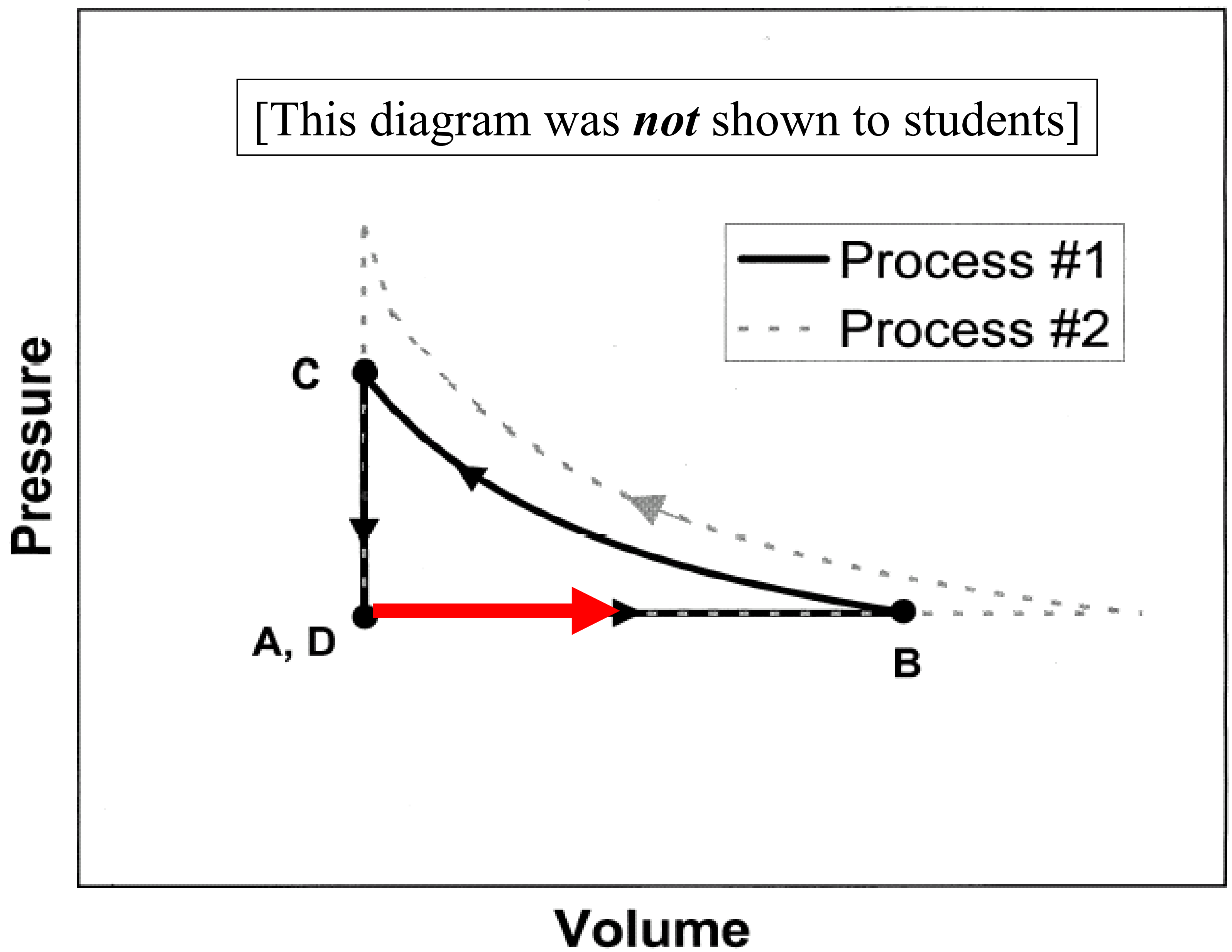
Time *B*

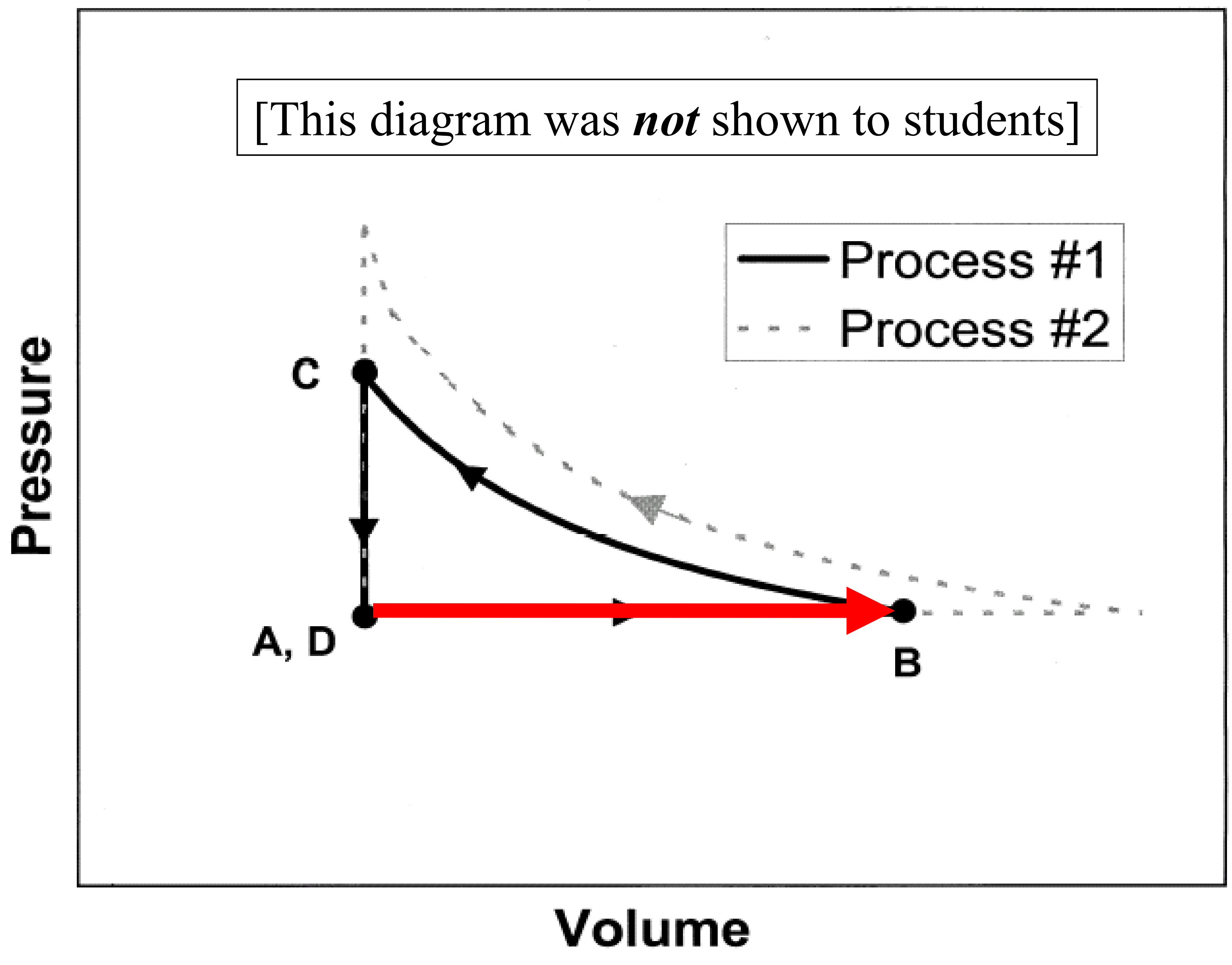
Piston in new position.

Temperature of system has changed.

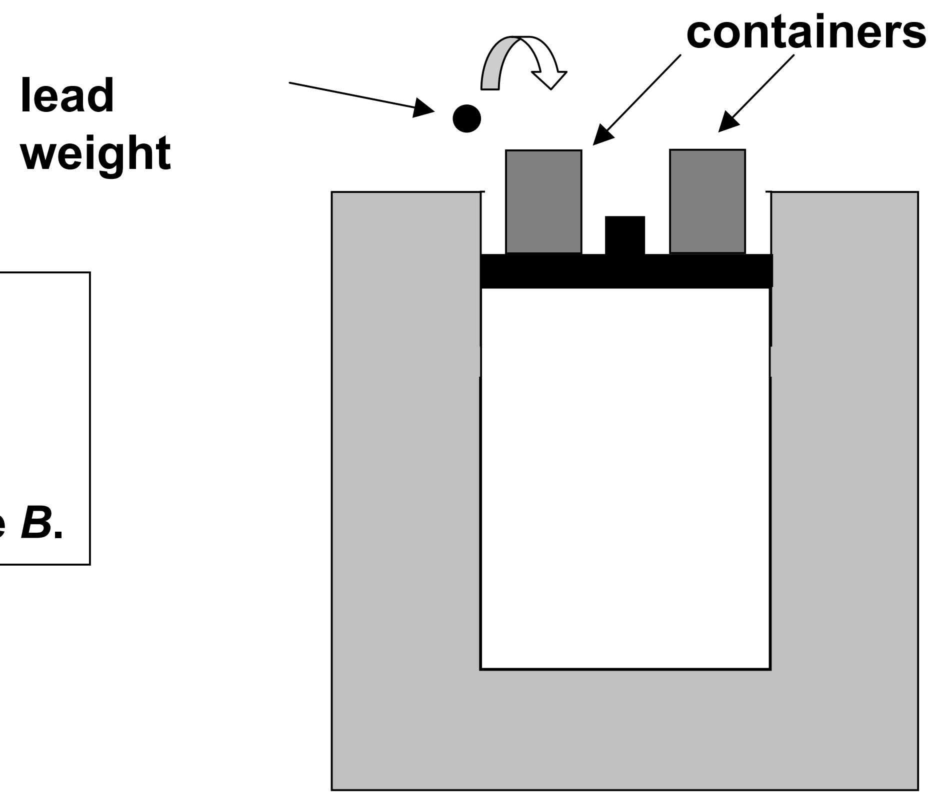



[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume


[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

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.)



weights being added

Piston moves down slowly.

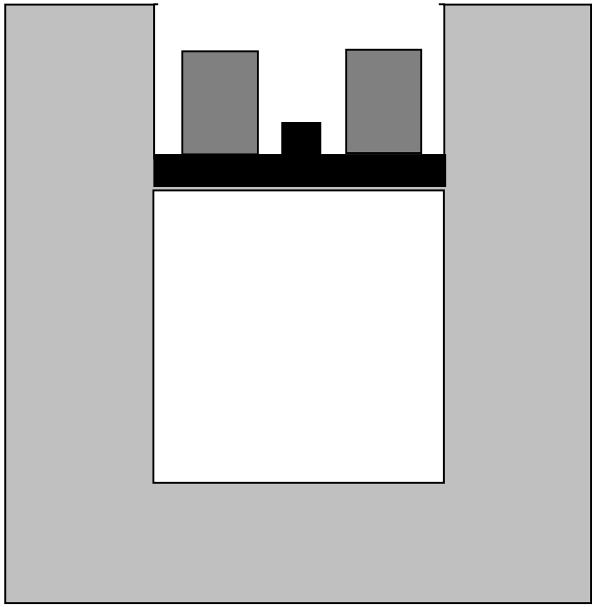
Temperature remains same as at time *B*.

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.)

weights being added

Piston moves down slowly.

Temperature remains same as at time *B*.



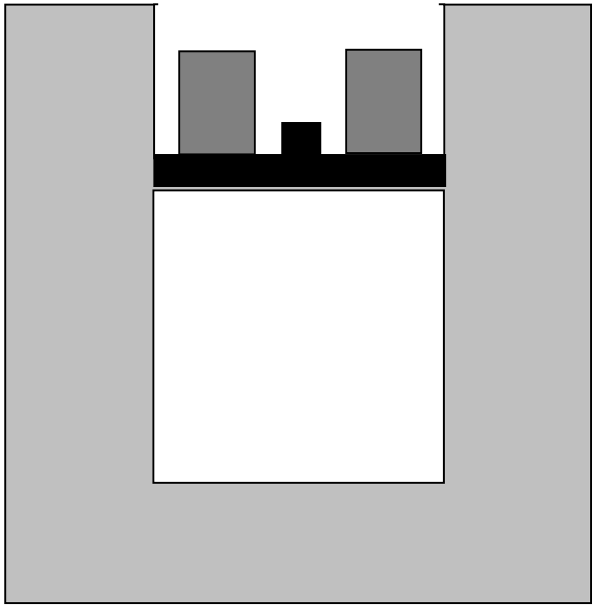
Step 3. At time *C* we stop adding lead weights to the container and the piston stops moving. (The weights that we have already added up until now are still in the containers.) The piston is now found to be at *exactly the same position it was at time **A*** .

Time *C*

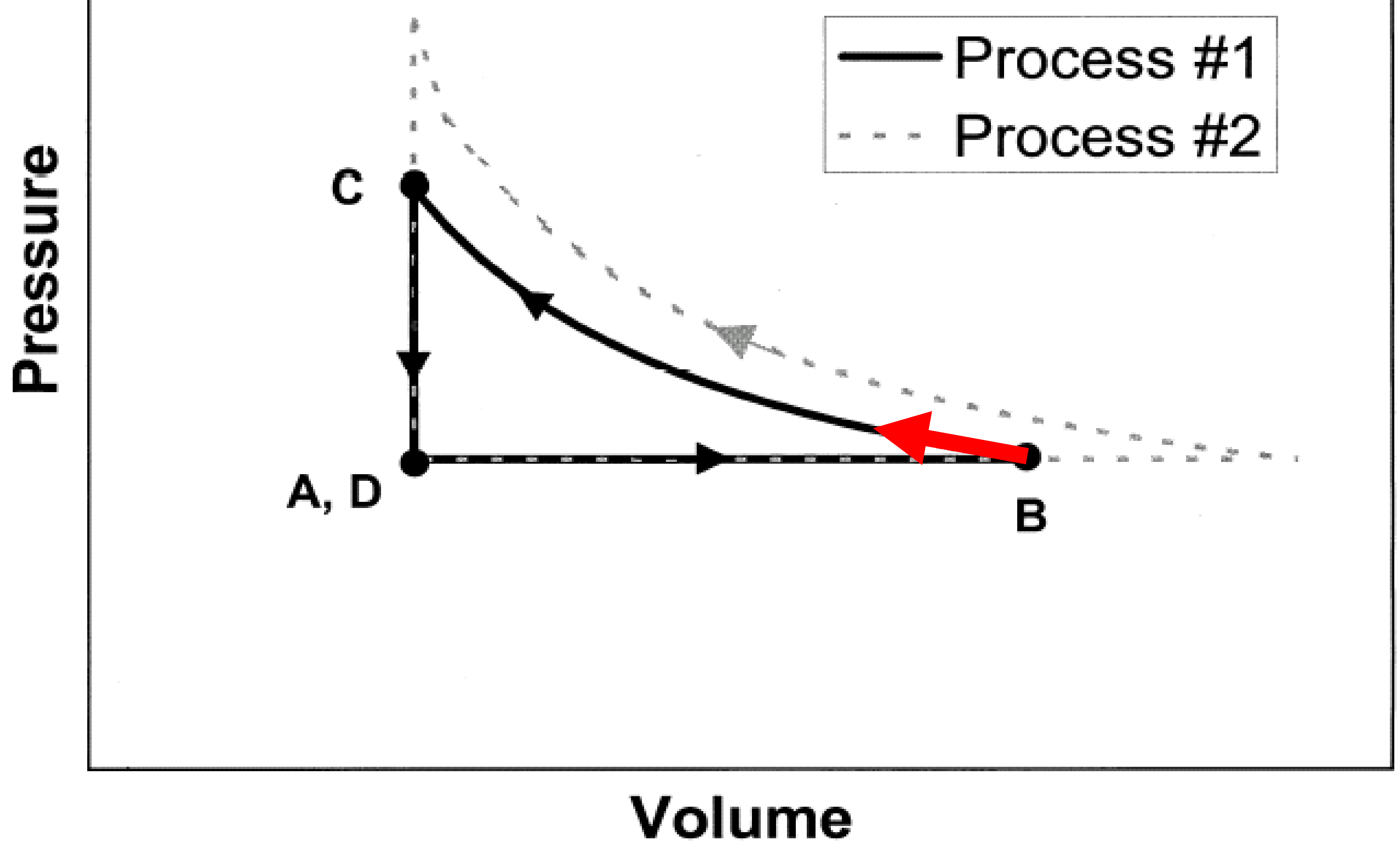
Weights in containers.

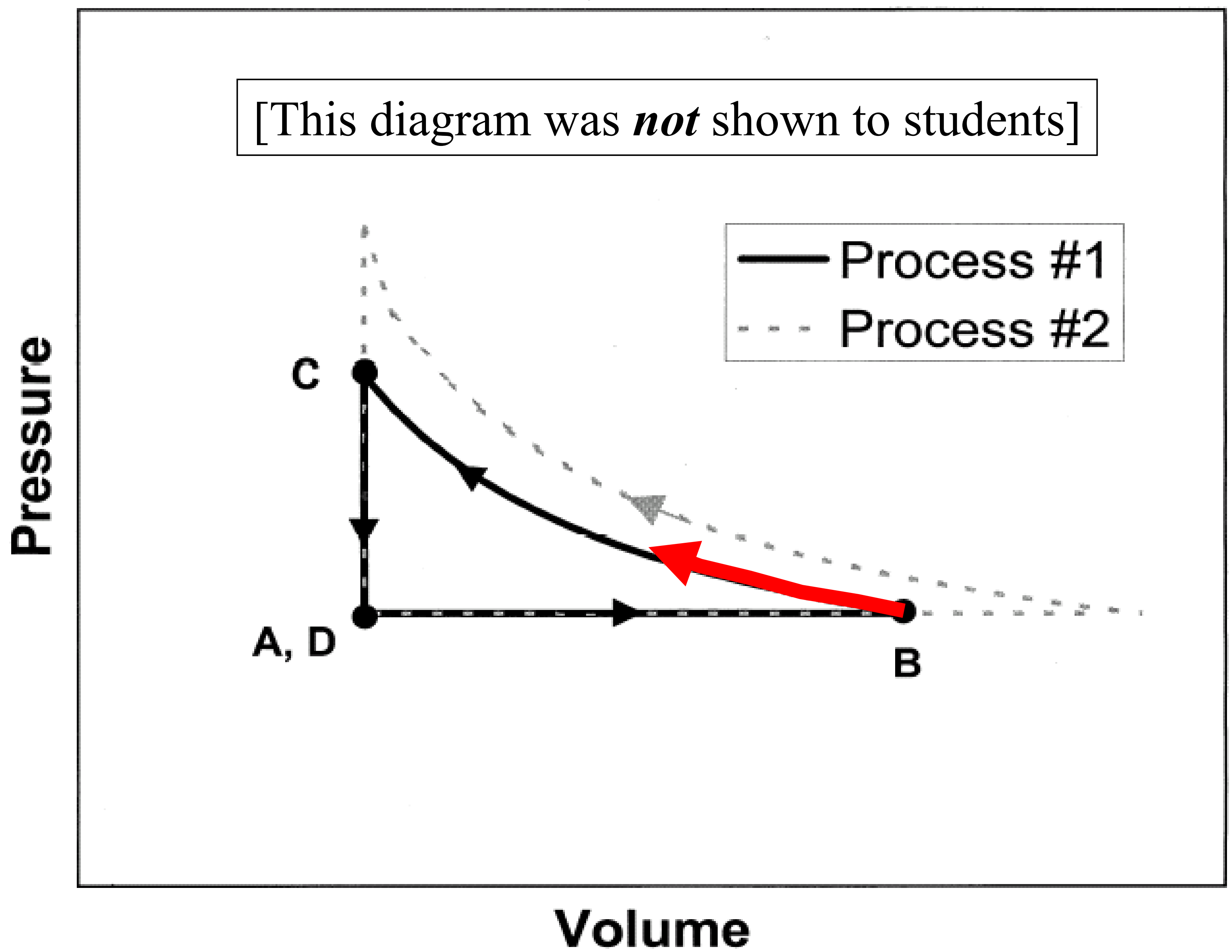
Piston in same position as at time *A*.

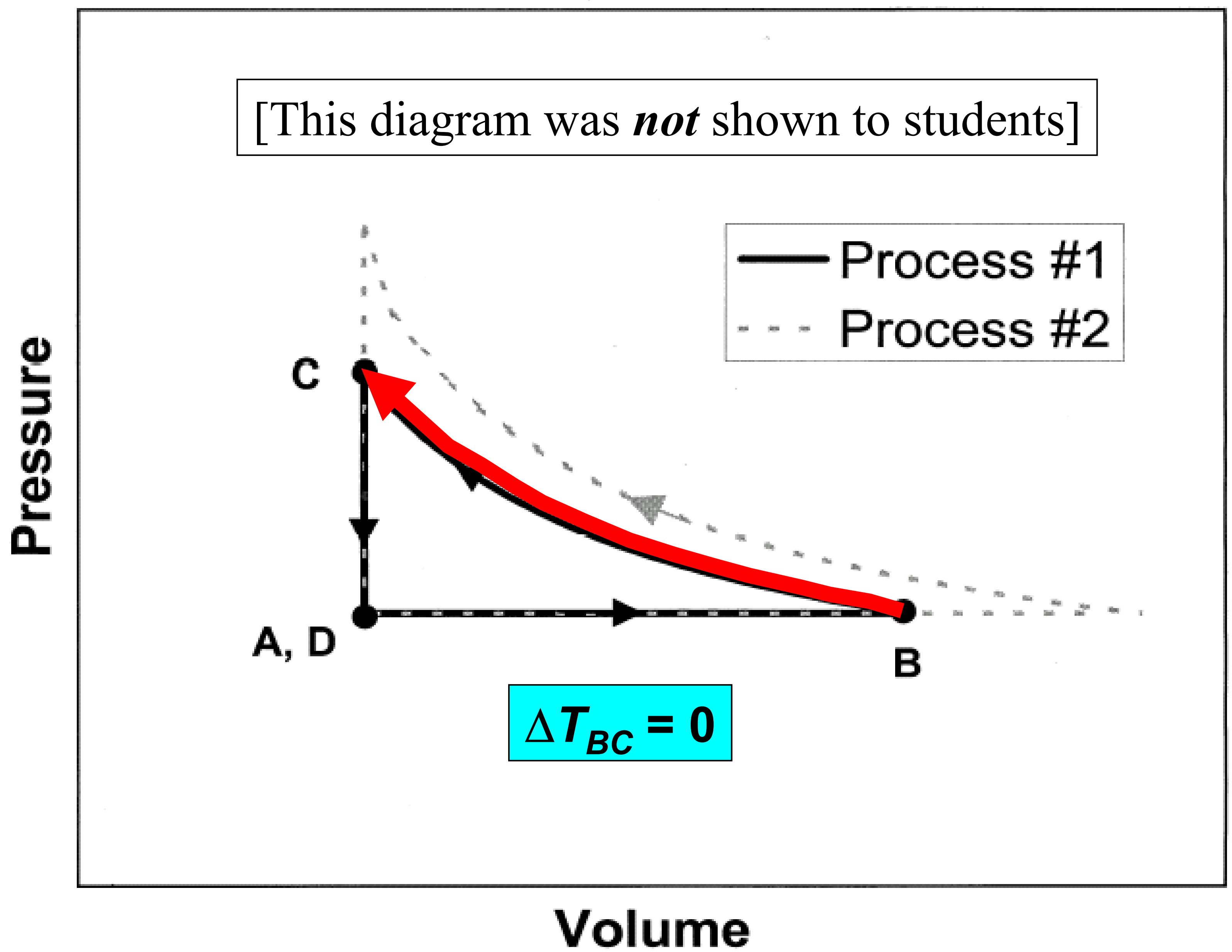
Temperature same as at time *B*.



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




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



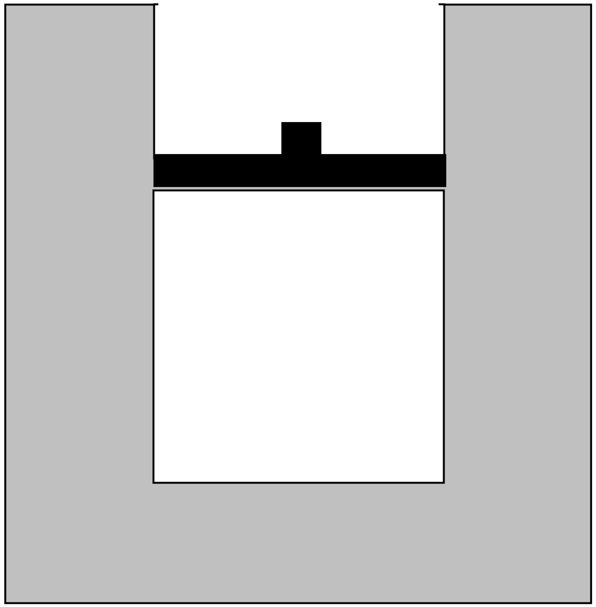
[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
$\Delta T_{BC} = 0$
Pressure
Volume

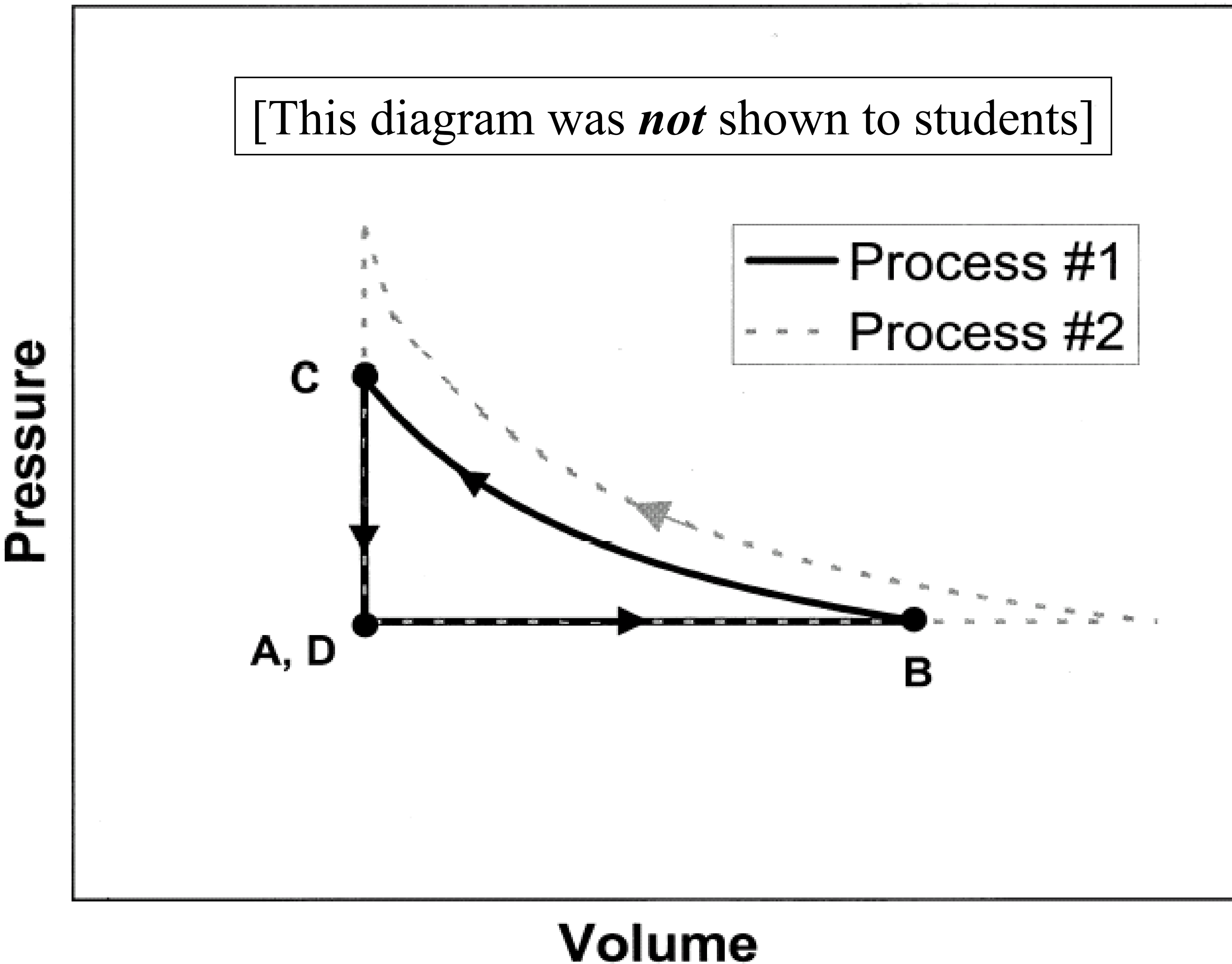
Step 4. Now, the piston is locked into place so it *cannot move*; the weights are removed from the piston. The system is left to sit in the room for many hours, and eventually the entire system cools back down to the same room temperature it had at time *A.* When this finally happens, it is time *D*.

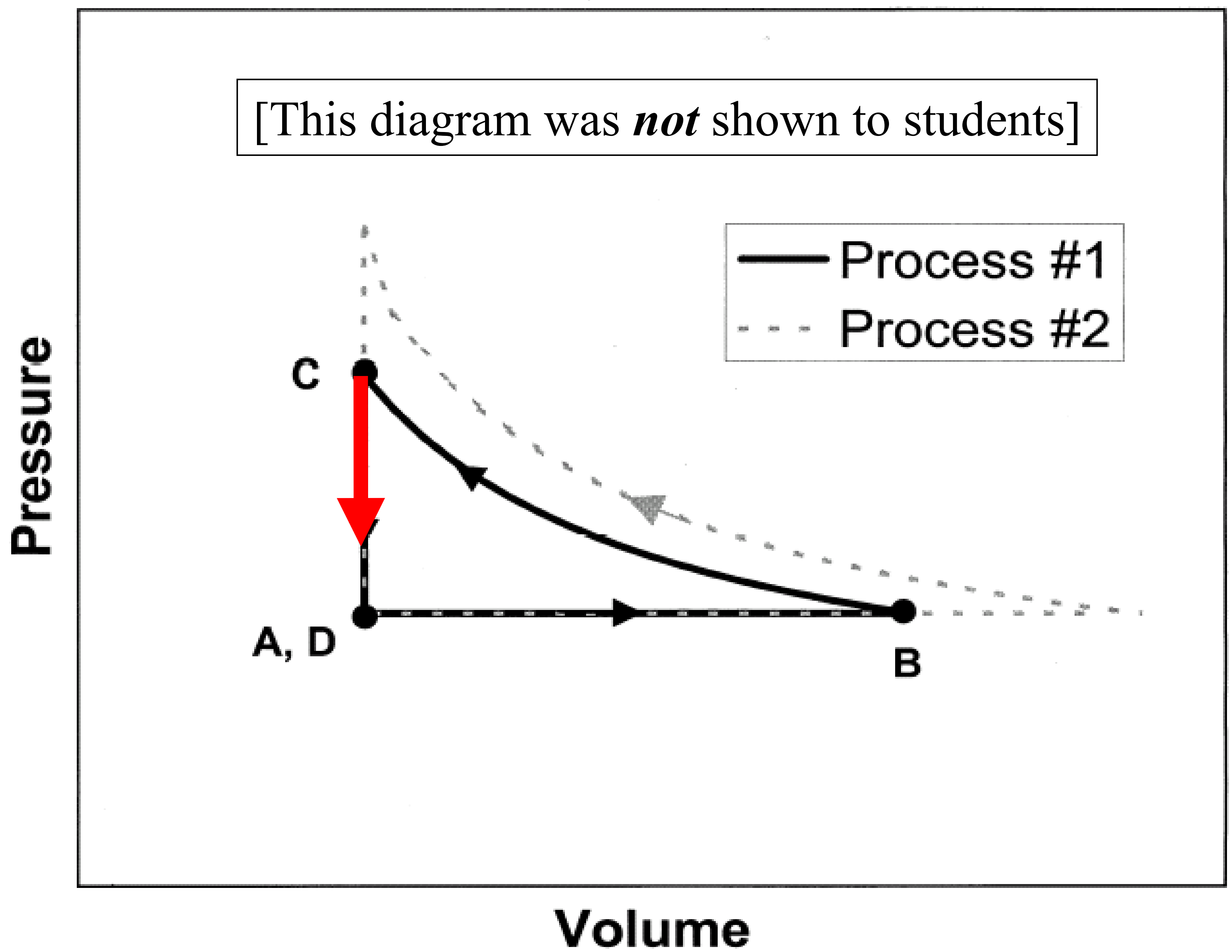
Time *D*

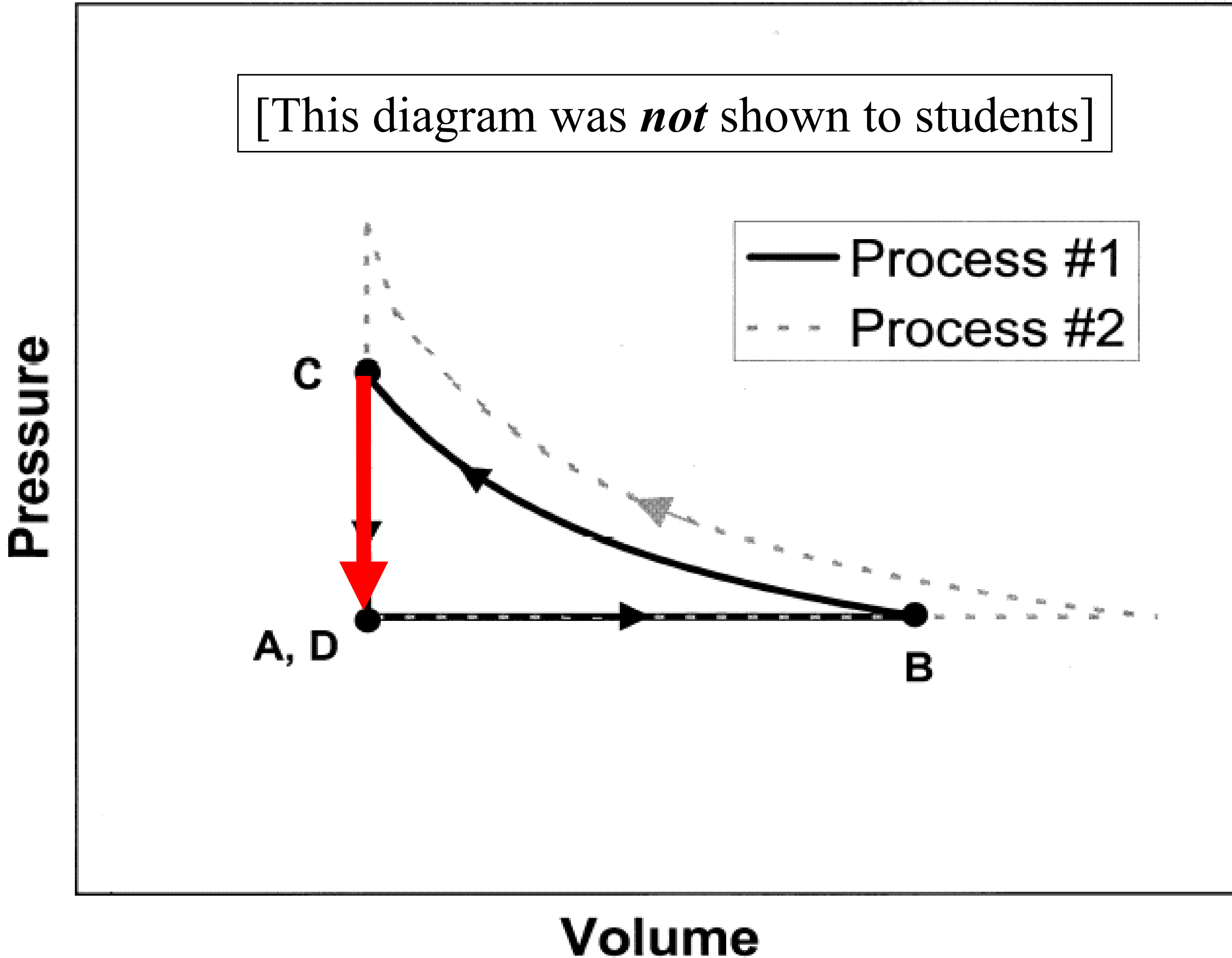
Piston in same position as at time *A*.

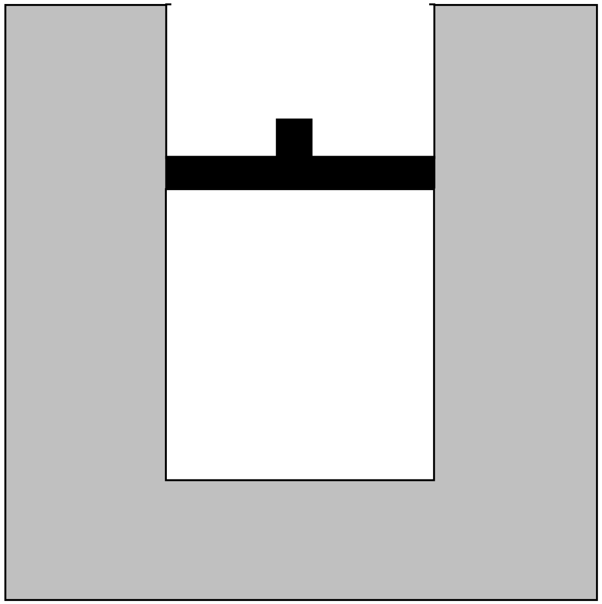
Temperature same as at time *A*.




[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
Pressure
Volume



Time *D*

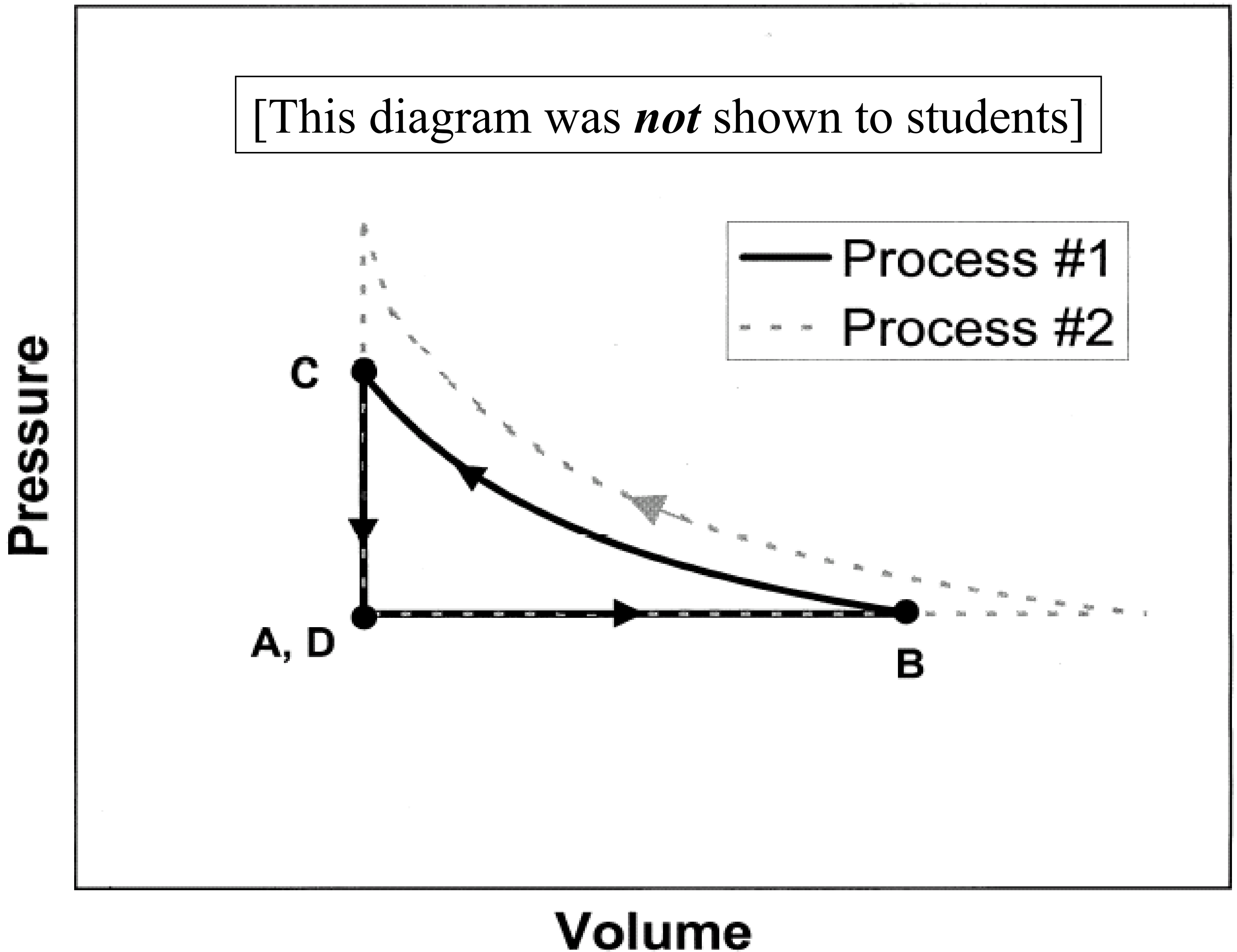
Piston in same position as at time *A*.

Temperature same as at time *A*.

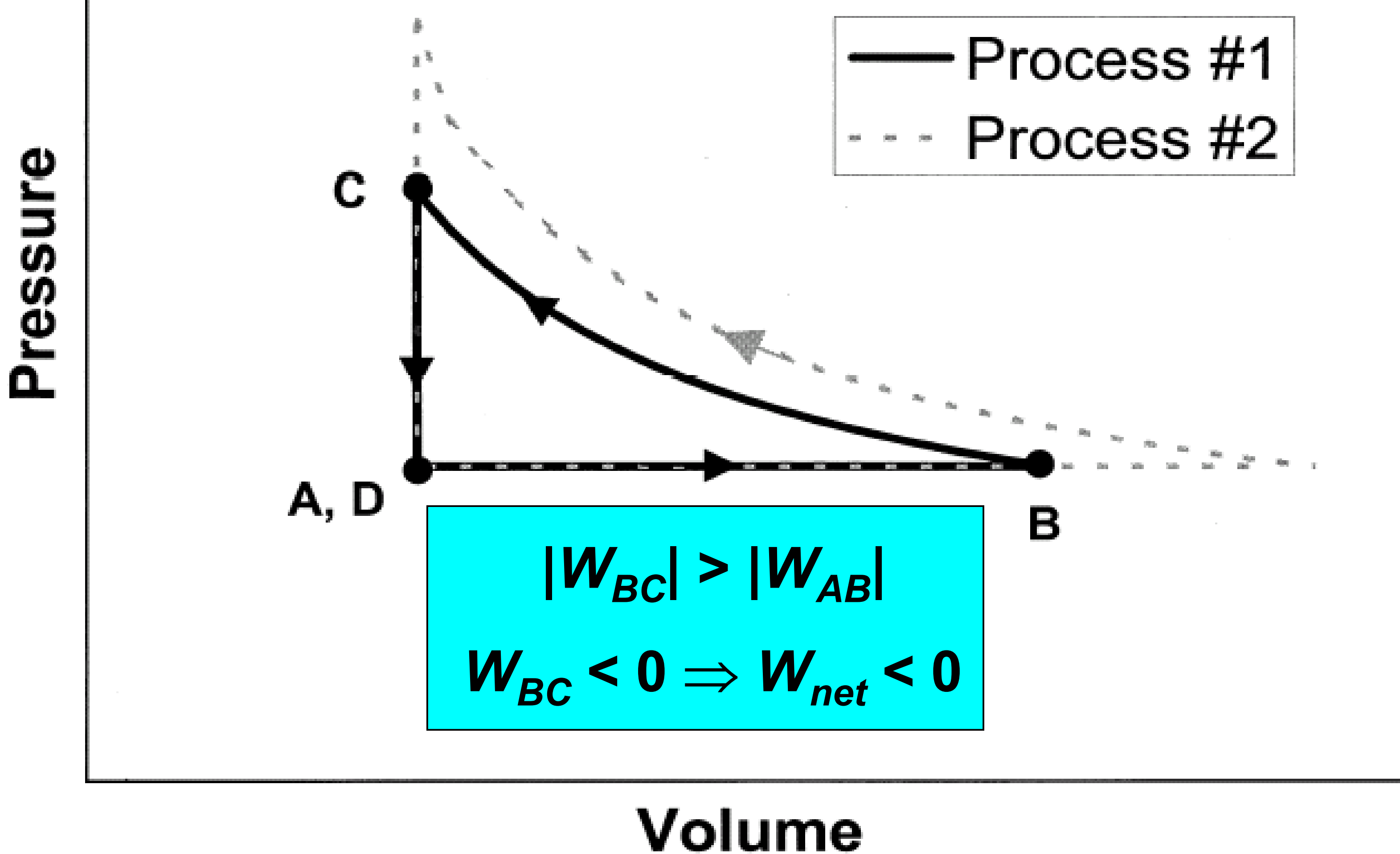
Question #6: Consider ***<u>the entire process</u>*** from time *A* to time *D*.

(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?

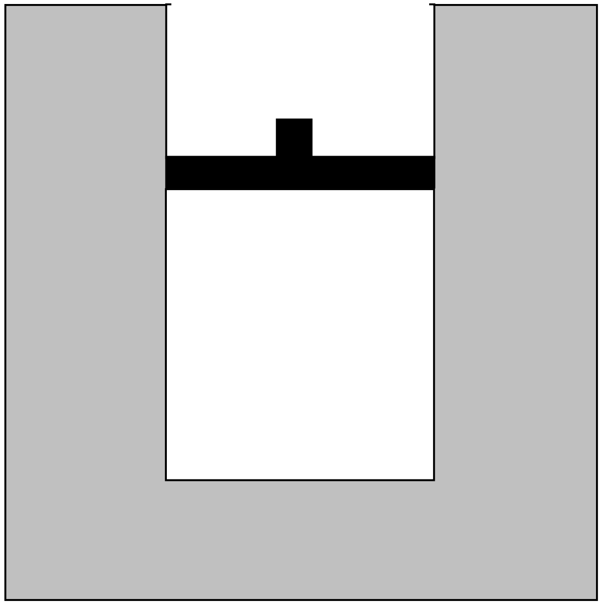

[This diagram was *not* shown to students]
Process #1
Process #2
C
A, D
B
Pressure
Volume

[This diagram was *not* shown to students]



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

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



Time *D*

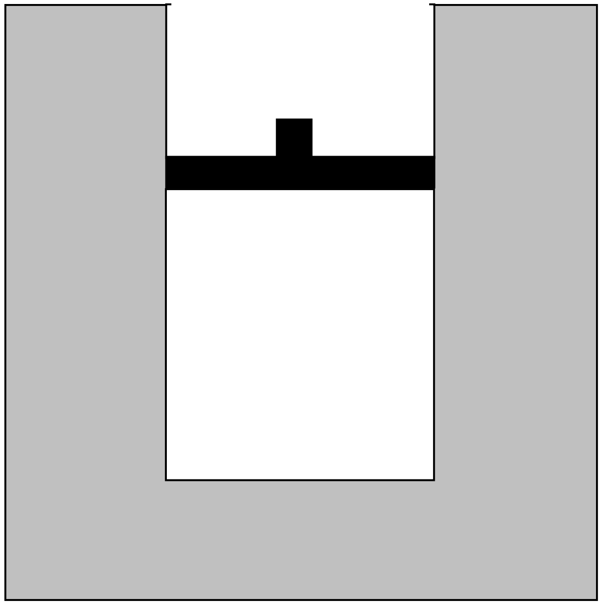
Piston in same position as at time *A*.

Temperature same as at time *A*.

Question #6: Consider ***<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?



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?

Results on Interview Question #6 (i)

$N = 32$

- Most students (more than two thirds) quickly and confidently answered that net work done would be equal to zero
- Explanations centered on two common themes:
  - *positive work (piston moves one way) cancels negative work (piston moves other way)*
  - *work depends on volume change, and there was no net change in volume*

Consistent with findings of Loverude, Kautz, and Heron (2002)

Explanations offered for $W_{net} = 0$

“[Student #1:] *The physics definition of work is like force times distance. And basically if you use the same force and you just travel around in a circle and come back to your original spot, technically you did zero work*.”

Explanations offered for $W_{net} = 0$

"[Student #1:] *The physics definition of work is like force times distance. And basically if you use the same force and you just travel around in a circle and come back to your original spot, technically you did zero work*."

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

Indications of Instability

- At end of interview, students were asked to draw a *P*-*V* diagram of the process
- About 20% of those students who initially answered “zero net work” spontaneously reconsidered their answer after drawing a *P*-*V* diagram, some changing to the correct answer.

Conceptual "Metastability"

- Belief in zero net work was expressed quickly, confidently, and with supporting arguments, ***but*** – reasoning was rarely precise, and was limited to simple formulations.
- For some students, belief was unstable even to *minimal* additional probing
- No evidence that conception was pre-formulated or had been consciously articulated in advance
- Although explanations were (apparently) worked out on the spot, most students obtained same answer with similar reasoning

Students' conception seems based in part on common-sense notion that system returned to its initial state must have at least some unchanged properties

however . . .

Students' reasoning also includes specific arguments based on prior knowledge of physics: must be addressed during instruction.

Although students' conception lacks stability of "alternative theory," it may turn out to be quite resistant to instruction nonetheless.

Investigating the Stability of a Learning Difficulty: An Example

- Naïve student conceptions often based on flawed distinction between two physical concepts (e.g., velocity/acceleration; current/voltage)
- Only vaguely or incompletely expressed until encountered in instructional setting
- Through research we map such confusions and the situations that often elicit them
- Frequently reproducible with monotonously predictable regularity

Investigating the Stability of a Learning Difficulty: An Example

Questions regarding heat absorbed by system:

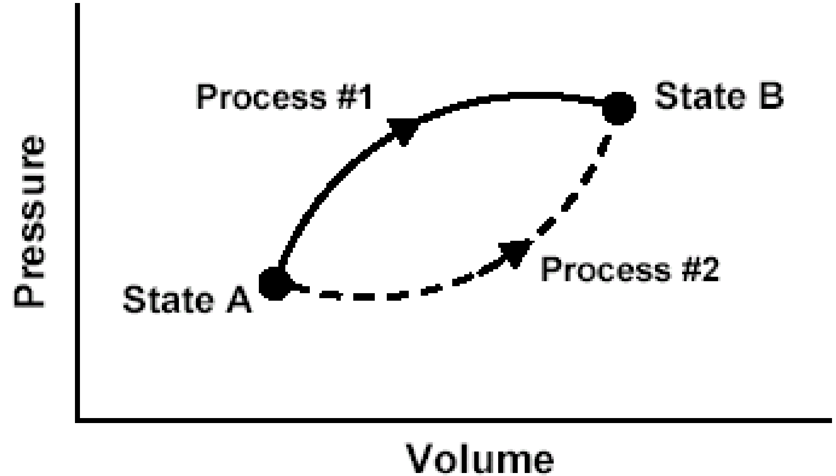
- Written question involving *P-V* diagrams (N = 653)
- Interview questions regarding net heat absorbed during cyclic process (N = 32)

Investigating the Stability of a Learning Difficulty: An Example

Questions regarding heat absorbed by system:

- Written question involving *P-V* diagrams (*N* = 653)
- Interview questions regarding net heat absorbed during cyclic process (*N* = 32)

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.]

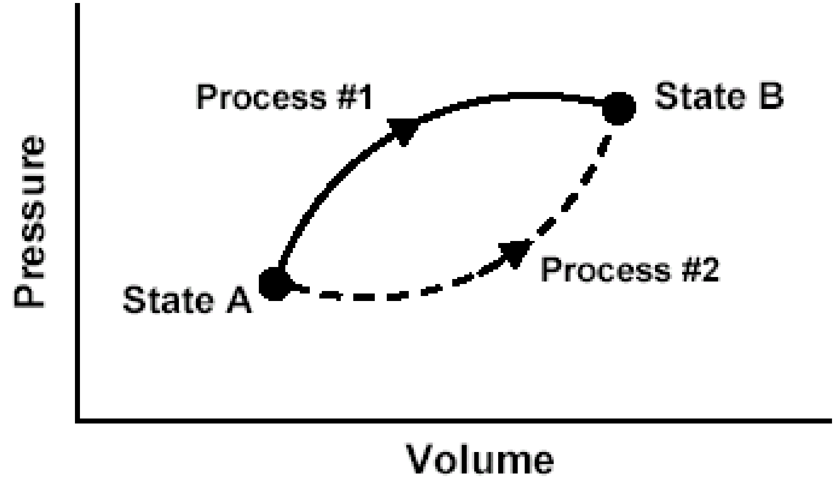
1. Is *W* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2? Explain.

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.]

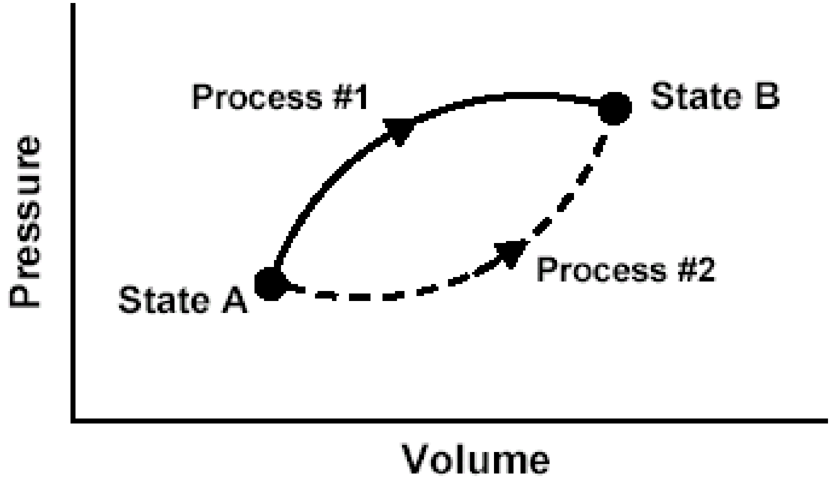
1. Is *W* for Process #1 ***greater than, less than***, or ***equal to*** that for Process #2? Explain.

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:

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?***

Examples of Acceptable Student Explanation 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*."

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:

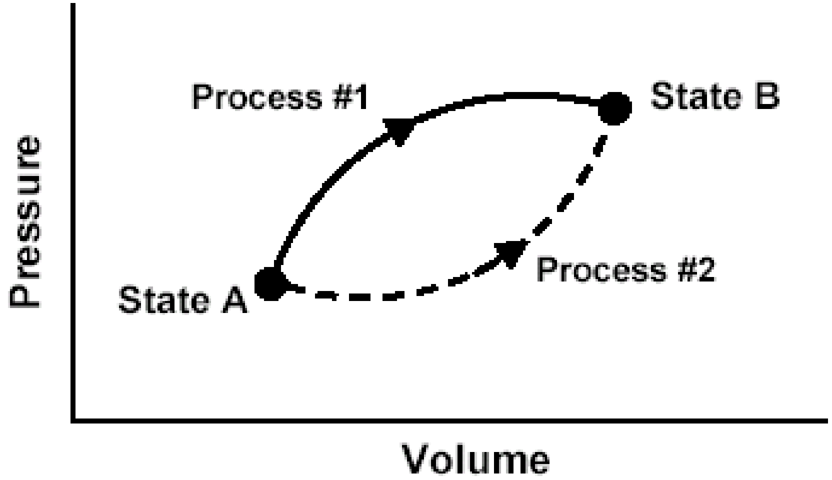
Algebraic Method:

$$\Delta U_1 = \Delta U_2$$

$$Q_1 - W_1 = Q_2 - W_2$$

$$W_1 - W_2 = Q_1 - Q_2$$

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



[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?***

Student Conception: Heat Behaves as State Function

- 38% of students giving written response, and 47% of interview subjects, asserted that $Q_1 = Q_2$
- Large proportion of students made ***explicit*** statements regarding path-independence of heat
  - 21% of students in written sample
  - 44% of students in interview sample

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

- "*I believe that heat transfer is like energy in the fact that it is a state function and doesn't matter the path since they end at the same point*."
- "*Transfer of heat doesn't matter on the path you take*."
- "*They both end up at the same PV value so . . . They both have the same Q or heat transfer*."

➢ **Almost 150 students offered arguments similar to these either in their written responses or during the interviews . . . Although they had never read it in a textbook or heard it from an instructor.**

Investigating the Stability of a Learning Difficulty: An Example

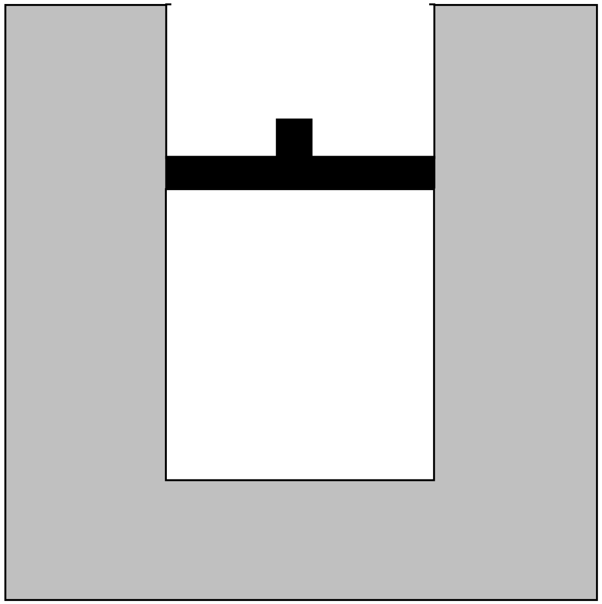
Questions regarding heat absorbed by system:

- Written question involving *P*-*V* diagrams (*N* = 653)
- Interview questions regarding net heat absorbed during cyclic process (*N* = 32)

Investigating the Stability of a Learning Difficulty: An Example

Questions regarding heat absorbed by system:

- Written question involving *P-V* diagrams (N = 653)
- Interview questions regarding net heat absorbed during cyclic process (N = 32)



Time *D*

Piston in same position as at time *A*.

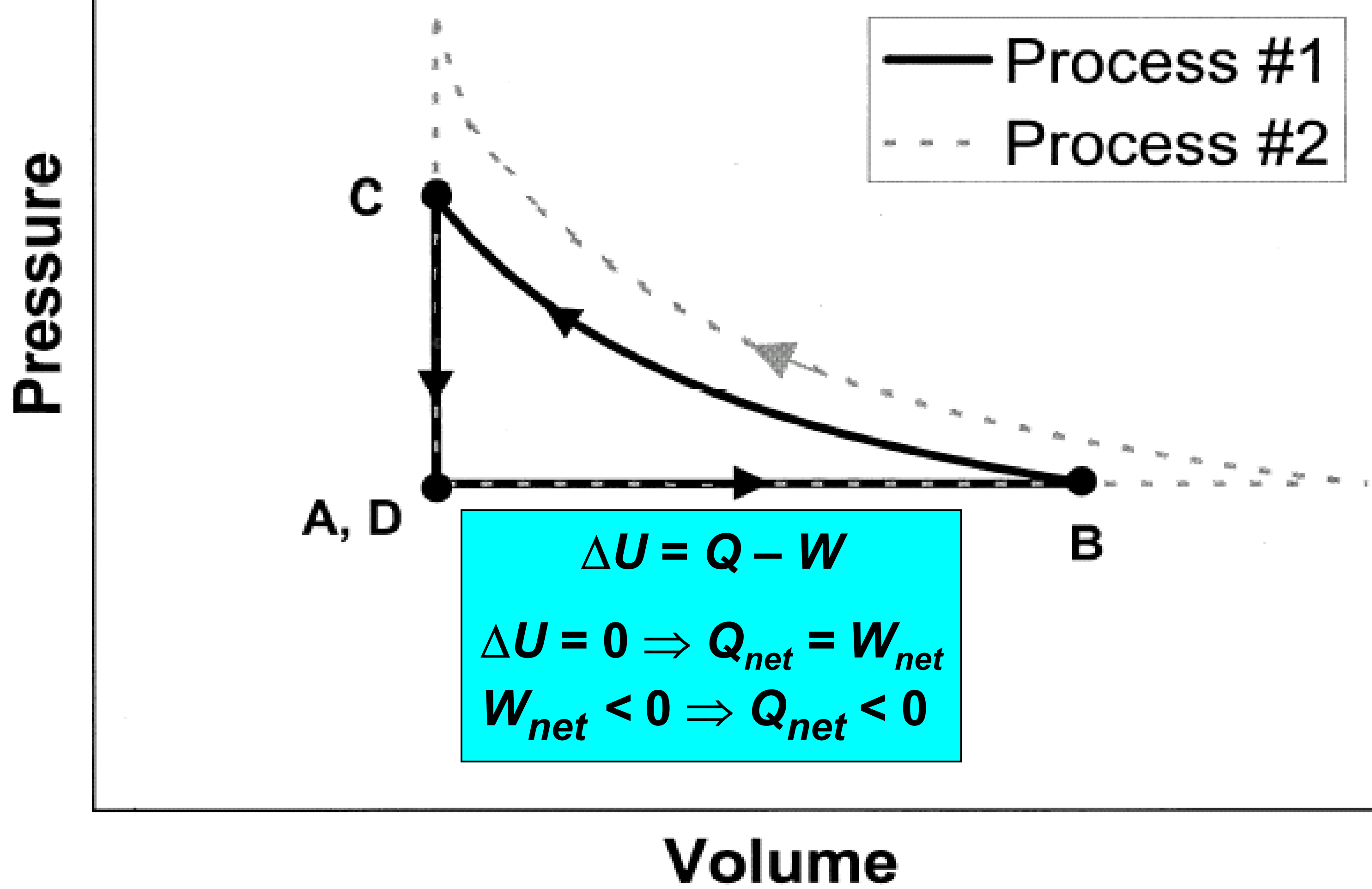
Temperature same as at time *A*.

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?

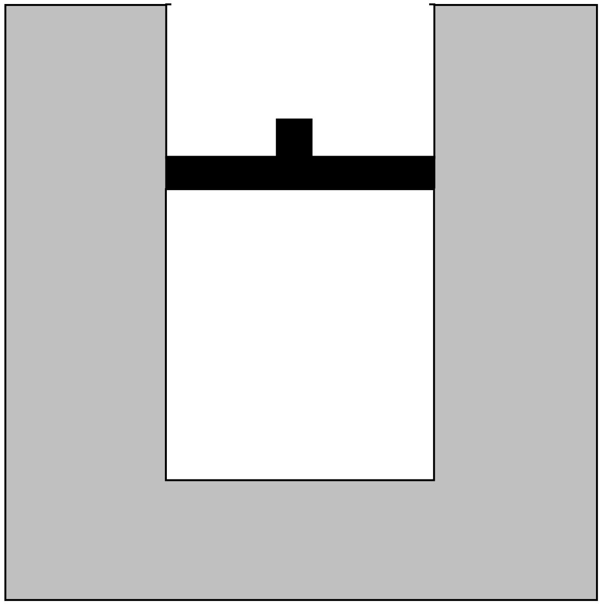
[This diagram was ***not*** shown to students]



$\Delta U = Q - W$

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

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



Time *D*

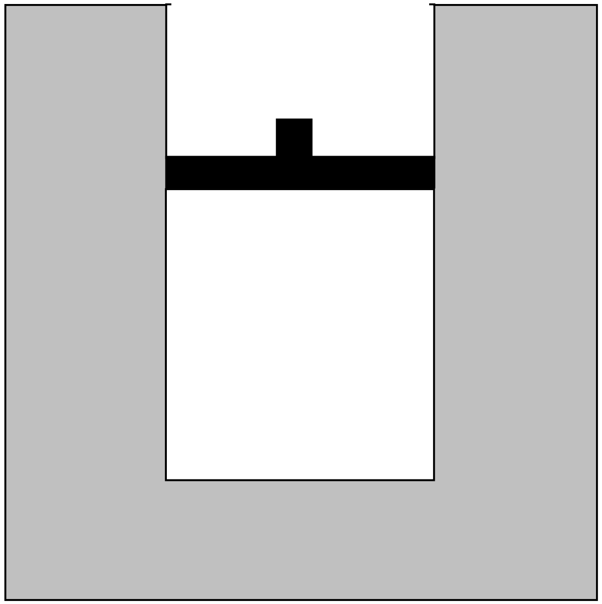
Piston in same position as at time *A*.

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 ***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 (ii)
$N = 32$

- More than two thirds (69%) of students said that net heat transfer was “equal to zero”
- Most based their arguments on identity between initial and final states, and on zero net change in temperature

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."*

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.*"

Responses in two different contexts extremely consistent, reflect student conception:

heat is or behaves as a state function

Follow-up Interview Question

- Students asked to rank absolute values of net work done by gas and total heat transferred to gas during cyclic process
- When discrepancy appeared between answers to this question and previous questions, students asked to resolve it
- 60% gave response consistent with $|Q_{total}| = 0$

Consistent with previous responses

A Popular Student Conception

- Many students ($N \approx 150$) made ***explicit*** statements to effect that heat was “a state function,” “doesn’t depend on path,” or “depends only on initial and final state”
- Such statements were synthesized by students on their own – never heard from instructor or read in text

What We Know and What We Don't (so far)

- Students' conception regarding heat evidently related to overgeneralization of correct understanding of state functions
- Precisely how this conception develops not yet known
- Nonetheless, there is great value simply in knowing:
  - that it does tend to occur
  - its approximate frequency of occurrence
  - the general form of students' explanations

Outline

- Objectives of the Endeavor
- A Model for Students' Knowledge
- Probing Students' Knowledge
- Applying the Model: Thermodynamics research project
- Learning Difficulties, Not Alternative Theories
- How do we know our analysis is correct?
- Summary

How do we know our interpretation of students' reasoning is accurate?

Interviews consist of minimal probing over period of time;

how should one interpret:

Initially correct response changed to incorrect response

and . . .

Incorrect changed to correct?

Not very unusual when probing the gray region

Assessment is Dynamic

- ***Primary issue:*** How to deduce students' content-specific learning trajectory (rate and direction) from snapshot in time
- For individual student assessment, *many* details are desirable:
  - Solidity of conceptual knowledge and of links
  - Methods of, and attitude toward, learning physics
  - Efficiency in synthesizing new concepts under guidance
  - *Etc.*

Characterizing a Population

For large numbers of students, need "ensemble" average or characteristic values of:

- Typical reasoning patterns
- Solidity of knowledge
- Degree of confidence
- Stability of links
- Responsiveness to probes

And: must gauge magnitude of line width (range of values)

(Potentially) Useful Data

- Statistical summary
  - Number and popularity of different lines of productive and unproductive reasoning
- Qualitative assessment
  - Potentially fruitful, partially understood concepts and intuitions
  - Consistency of various assessments
    - Interviews, written diagnostics, multiple-choice, etc.
  - Stability of students' responses
  - Students' confidence in their responses
  - Other common themes not in quantitative data

Points of Attention

- Does students’ use of mathematical calculations obscure gaps in conceptual reasoning? (Or do minor errors obscure good qualitative understanding?)
- Are selected quotations reasonably representative of full student sample?
- Remember: however potentially misleading, interviews represent real and meaningful evidence of students’ knowledge state

Outline

- Objectives of the Endeavor
- A Model for Students' Knowledge
- Probing Students' Knowledge
- Applying the Model: Thermodynamics research project
- Learning Difficulties, Not Alternative Theories
- How do we know our analysis is correct?
- Summary

Summary

- We are probing student thinking that is in a state of flux and development
- Students' understanding is metastable, undergoing evolution and restructuring
- Aim of research is not to portray picture of firmly rooted student concepts, but to provide snapshot of evolving ideas:
  - that which is clearly defined and persistent
  - that which is flexible and fluid