Problem-property dependence of students' responses to thermodynamics problems

David E. Meltzer
Arizona State University

Mary Jane Brundage
Misericordia University

Chandralekha Singh
University of Pittsburgh

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Investigating the impact of problem properties on introductory and advanced student responses to introductory thermodynamics conceptual problems

Mary Jane Brundage,[1] David E. Meltzer,[2] and Chandralekha Singh[1]

[1]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pittsburgh 15260, USA*
[2]*College of Integrative Sciences and Arts, Arizona State University, Mesa, Arizona 85212, USA*

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Exploring students' thinking when solving thermodynamics problems

- **78-item Multiple-choice instrument:** "Survey of Thermodynamic Processes and First and Second Laws (STPFaSL-Long)"
  - administered after instruction in standard algebra- and calculus-based lecture courses
- Each individual thermodynamics concept was targeted by 2-5 different problems
- Problems differ from each other by:
  - using diverse physical settings and scenarios
  - very minor changes in wording or in diagrammatic features
  - including diverse potentially distracting features
- Sample size ranged from 320-550 (varied by problem)
- With these sample sizes, differences in correct-response rates ≈15% or greater are statistically significant, generally with $p<0.001$ and effect size > 0.3
- **Interview data**: Interviews carried out with 17 students (11 introductory; 6 upper-level)

Targeted Concepts (among others)

(E= internal energy; W = work done *by* system; Q = heat transfer *to* system)

- E is proportional to T for an ideal gas
- The sign of ΔE for an ideal gas is determined by whether the product PV is increasing or decreasing
- W is positive for an expansion

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Information provided to students on first page:

Survey of Thermodynamic Processes and First and Second Laws (STPFaSL-Long)

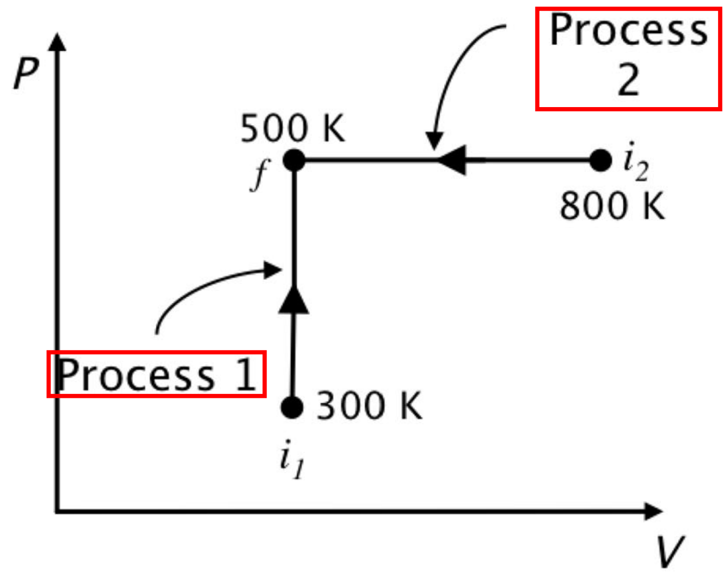
- Please select only one of the four choices, (a)-(d) or True/False for each of the questions.
- All temperatures T are absolute temperatures.
- All experiments involving a gas as the system are performed with a fixed amount of gas.
- The following equations may be useful for an ideal monatomic gas system where the symbols have the usual meaning: the internal energy $E_{int} = (3/2)NkT$ and $PV = NkT$.
- Thermal reservoirs are significantly larger than the system so that heat transfer between the system and the reservoir does not change the temperature of the reservoir.
- An adiabatic process is one in which there is no heat transfer between a system and its surroundings.
- The process described in questions 60-62 is quasi-static. A quasi-static process passes through a sequence of equilibrium states.

The following abbreviations are used throughout the survey:

- W = work done by the system.
- Q = net heat transfer to the system.

Also, Q_1, Q_2 in a particular problem will refer to the net heat transfer to the system in process 1 and process 2, respectively, etc.

You carry out two experiments each with one mole of an ideal monatomic gas such that both processes end in the same state shown on the PV diagram below. Process 1 is a constant volume process starting at 300K at point i_1 and ending at point f at 500K whereas process 2 is a constant pressure process starting at 800K at point i_2 and ending at point f at 500K. Answer the following two questions about these experiments:



(33) Which one of the following statements is true about the change in the internal energy of the gas for process 1?

a. Internal energy does not change for process 1.
b. Internal energy increases for process 1.
c. Internal energy decreases for process 1.
d. Not enough information.

Answer: (b); temperature increases so internal energy increases.
Correct-response rate; Calculus-based: 76%; Algebra-based: 81%

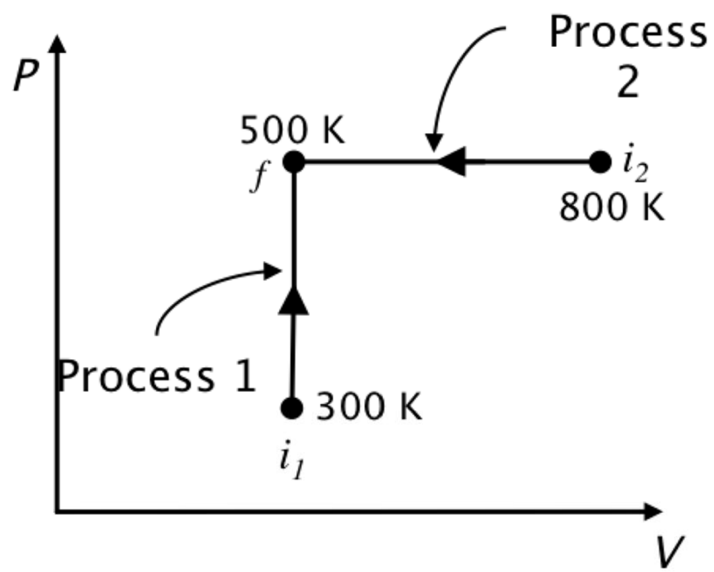
(34) Which one of the following statements is true about the change in the internal energy of the gas for process 2?

a. Internal energy does not change for process 2.
b. Internal energy increases for process 2.
c. Internal energy decreases for process 2.
d. Not enough information.

Many more errors on #34 (Process 2) →

Answer: (c); temperature decreases so internal energy decreases.
Correct-response rate; Calculus-based: 58%; Algebra-based: 55%

Why did students make significantly more errors on #34?



Interviews: 3 of 6 students who gave incorrect answer on #34 (Process 2) argued "Work done is negative so internal energy will increase"

This would be true for an adiabatic *process; however, students have completely ignored the role of heat transfer (Q < 0 in this case).*

Students were distracted by work considerations; this was also true for Process 1 (zero work) but not, apparently, to the same degree as in Process 2.

The salience of the negative-work feature in Process 2 seems to have played a key role in students' thinking.

(34) Which one of the following statements is true about the change in the internal energy of the gas for process 2?

a. Internal energy does not change for process 2.
b. Internal energy increases for process 2.
c. Internal energy decreases for process 2.
d. Not enough information.

Answer: (c); temperature decreases so internal energy decreases.

Correct-response rate; Calculus-based: 58%; Algebra-based: 55%

The use of a horizontal arrow on a *PV* diagram (instead of an arrow pointed straight up) lured some students into unproductive considerations regarding *work*, lowering the correct-response rate by 18-26%.

Targeted Concepts (among others)

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- The following equations may be useful for an ideal monatomic gas system where the symbols have the usual meaning: the internal energy $E_{int} = (3/2)NkT$ and $PV = NkT$.
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- An adiabatic process is one in which there is no heat transfer between a system and its surroundings.
- The process described in questions 60-62 is quasi-static. A quasi-static process passes through a sequence of equilibrium states.

The following abbreviations are used throughout the survey:

- W = work done by the system.
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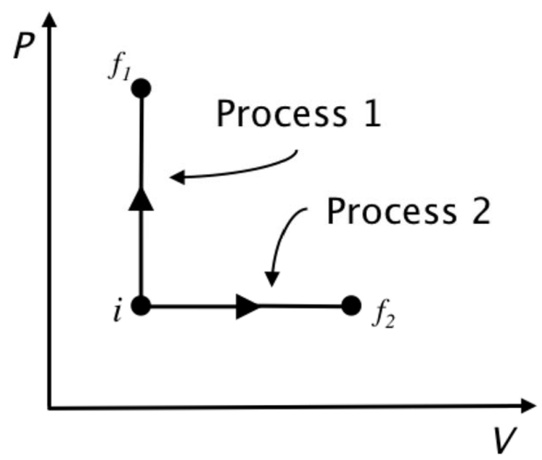
Also, Q_1, Q_2 in a particular problem will refer to the net heat transfer to the system in process 1 and process 2, respectively, etc.

You carry out two experiments each with one mole of an ideal monatomic gas such that both processes start in the same state i as shown on the PV diagram below. Process 1 is a constant volume (isochoric) process and process 2 is a constant pressure (isobaric) process. Answer the following six questions about the two processes:



(44) Which one of the following statements is correct about the change in internal energy of the gas in process 1?

a. There is no change in the internal energy of the gas in process 1.
b. The internal energy of the gas increases in process 1.
c. The internal energy of the gas decreases in process 1.
d. Not enough information.

(45) Which one of the following statements is correct about the change in internal energy of the gas in process 2?

a. There is no change in the internal energy of the gas in process 2.
b. The internal energy of the gas increases in process 2.
c. The internal energy of the gas decreases in process 2.
d. Not enough information.

Answer to *both* #44 and #45: (b); *PV* increases so internal energy increases [$E_{int} = (3/2)\ NkT = (3/2)\ PV$].

Correct-response rate on Process 1, Calculus-based: 69%; Algebra-based: 70%

Correct-response rate on Process 2, Calculus-based: 43%; Algebra-based: 37% ← *More incorrect answers on Process 2*

Interviews: 7 of 9 incorrect responses on Process 2 were justified by saying work done is positive so energy would decrease, thus ignoring the role of heat transfer.

For Process 2, the salience of the right-pointing horizontal arrow indicating that positive work is done lured students into flawed arguments regarding work and ignoring heat transfer.

The use of a horizontal arrow on a *PV* diagram (instead of an arrow pointed straight up) lured students into unproductive considerations regarding *work*, lowering the correct-response rate by 26-33%.

Targeted Concepts (among others)

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- W = work done by the system.
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Also, Q_1, Q_2 in a particular problem will refer to the net heat transfer to the system in process 1 and process 2, respectively, etc.

An ideal gas is allowed to undergo an isothermal expansion. Answer the following three questions about this process.

(62) Which one of the following statements is true about the work done by the gas in this process?

a. The work done by the gas is positive.
b. The work done by the gas is negative.
c. The work done by the gas is zero.
d. Not enough information.

Correct-response rate
Calculus-based: 65%; Algebra-based: 55%

Work = 0 responses
Calculus-based: 11%; Algebra-based: 16%

You perform an experiment with a gas such that it undergoes a reversible adiabatic expansion. Answer questions (1) - (3) below about this experiment.

(3) Which one of the following statements must be true for the work done by the gas that undergoes a reversible adiabatic expansion process?

a. The work done by the gas must be positive.
b. The work done by the gas must be negative.
c. The work done by the gas must be zero.
d. Not enough information.

Correct-response rate
Calculus-based: 54%; Algebra-based: 41%

Lower correct-response rate

Work = 0 responses
Calculus-based: 19%; Algebra-based: 27%

More W = 0 responses

An ideal gas is allowed to undergo an isothermal expansion. Answer the following three questions about this process.

(62) Which one of the following statements is true about the work done by the gas in this process?

a. The work done by the gas is positive.
b. The work done by the gas is negative.
c. The work done by the gas is zero.
d. Not enough information.

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c. The work done by the gas must be zero.
d. Not enough information.

Correct-response rate
Calculus-based: 54%; Algebra-based: 41%

Lower correct-response rate

Work = 0 responses
Calculus-based: 19%; Algebra-based: 27%

More W = 0 responses

More Work = 0 responses on "reversible adiabatic" expansion question

Interviews: Most incorrect answers on #3 were justified by Q = 0 arguments

The replacement of the word *isothermal* by the term *reversible adiabatic* lowered the correct-response rate by 11-14%, even though both processes were described as an "expansion."

General Findings

- Horizontal process arrows on *PV* diagrams often triggered unproductive lines of reasoning regarding work
- Certain terms may trigger unproductive lines of reasoning (e.g., *adiabatic*)
- Students tend to focus attention on the “most salient” variable (such as heat in an adiabatic process) while ignoring other variables

What makes a problem hard(er)?

- Use of potentially misleading/distracting diagrammatic elements
- Inclusion of (potentially misleading) irrelevant or redundant information
- Use of symbols in place of numbers (e.g., *m* or *μ* for *mass*)
- Need for unfamiliar or unpracticed mathematical skills
- Multiple relevant factors or variables in same problem (e.g., *E*, *Q*, *W*)
- Need for spatial reasoning (e.g., right-hand rules in magnetism)
- Dependence on or use of unfamiliar or subtle assumptions or terms
  - e.g., *adiabatic*, *thermal reservoir*, *quasi-static*, *reversible, spontaneous*
- Use of quantities with different defining equations in different contexts
  - e.g., $Q = mc\Delta T$ in calorimetry, but also $Q = \Delta U + W \neq 0$ even when $\Delta T = 0$)

Implications of Findings

- Minor changes to problem properties can lead to vastly different correct-response rates.
- Certain specific elements of diagrams or terminology can divert students into long chains of unproductive reasoning.
- Immediate “intuitive” responses often trigger lengthy chains of “off-track” unproductive reasoning.
- Focused instructional guidance may be needed to aid students in addressing these challenges.