Investigation of context dependence of students' responses to thermodynamics problems and its potential application to dual-process theory research

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(appearing soon...)

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

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Exploring students' thinking when solving thermodynamics problems

- We explored students' responses to a wide variety of problem types, such that 2-5 different problems all target the same physics concept; 13 different thermodynamics concepts serve as the targets. The problems differ from each other by using diverse physical settings and scenarios, as well as various types of potentially distracting features.

- **Multiple-choice instrument:** "Survey of Thermodynamic Processes and First and Second Laws (STPFaSL-Long)"; 78 problems in all; administered after instruction in standard lecture courses.

- Sample size ranges (varied by item)
  - Calculus-based introductory physics courses: 320-491
  - Algebra-based introductory physics courses: 331-550

- 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)

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.

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 undergoing an isochoric or isobaric process is determined by whether pressure or volume are increasing
- W is positive for an expansion whether adiabatic or isothermal
- In a reversible isothermal process, $Q \neq 0$ and the sign of Q is determined by whether volume is increasing or decreasing

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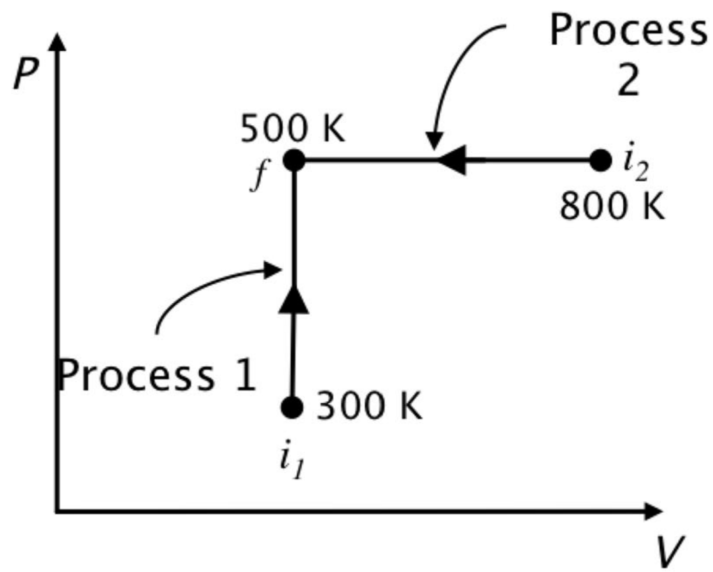
You carry out two experiments each with one mole of an ideal monatomic gas such that both processes end in the same state shown on the PV diagram below. Process 1 is a constant volume process starting at 300K at point i_1 and ending at point f at 500K whereas process 2 is a constant pressure process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

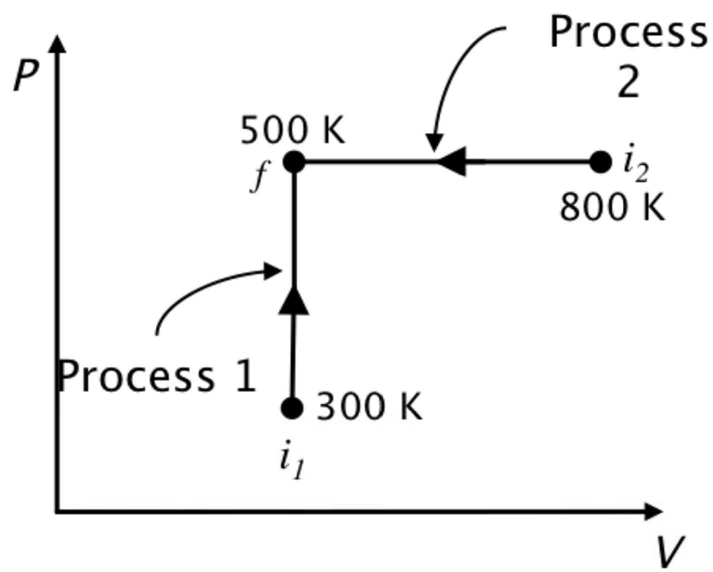
(34) Which one of the following statements is true about the change in the internal energy of the gas for process 2?

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.

More errors on #34 →

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.

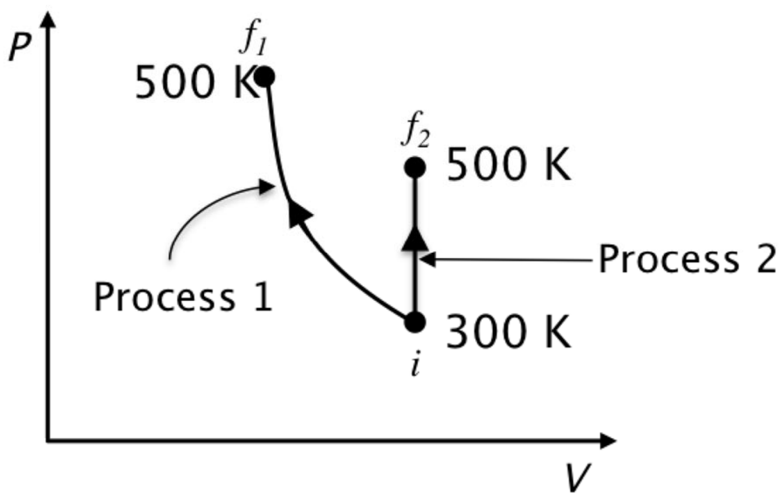
(34) Which one of the following statements is true about the change in the internal energy of the gas for process 2?

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%

You carry out two experiments each with one mole of an ideal monatomic gas. Both processes start at 300K at the same point i and both end at 500K but at different points f_1 and f_2 as shown on the PV diagram below. Processes 1 and 2 are adiabatic and isochoric (constant volume), respectively. Answer the following two questions about these experiments:



(69) Which one of the following statements is true about the change in the internal energy of the gas in these processes?

a. The change in the internal energy of the gas is equal for Processes 1 and 2.
b. The change in the internal energy of the gas is greater for Process 1 than Process 2.
c. The change in the internal energy of the gas is less for Process 1 than Process 2.
d. Not enough information.

Answer: (a); temperature changes are equal so internal energy changes are equal. *preferred*

Respondents choosing "b" (Process 1 change is greater), Calculus-based: 41%; Algebra-based: 51%

Respondents choosing "c" (Process 2 change is greater), Calculus-based: 25%; Algebra-based: 20%

Interviews: 3 of 5 students who answered "b"or "c" provided incorrect arguments regarding work.

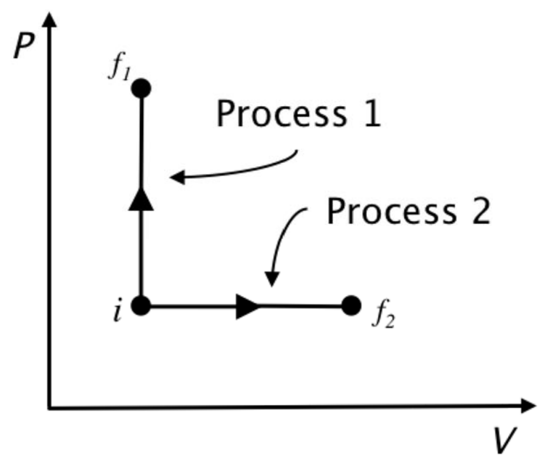
Students were distracted by work considerations based on the shape and direction of the process arrows; the Process 1 arrow may have been more salient, thus attracting more incorrect responses.

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 undergoing an isochoric or isobaric process is determined by whether pressure or volume are increasing
- W is positive for an expansion whether adiabatic or isothermal
- In a reversible isothermal process, $Q \neq 0$ and the sign of Q is determined by whether volume is increasing or decreasing

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 arrow indicating that positive work is done lured students into flawed arguments regarding work and ignoring heat transfer.

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 undergoing an isochoric or isobaric process is determined by whether pressure or volume are increasing
- *W* is positive for an expansion whether adiabatic or isothermal
- In a reversible isothermal process, $Q \neq 0$ and the sign of *Q* is determined by whether volume is increasing or decreasing

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%

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

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

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

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 undergoing an isochoric or isobaric process is determined by whether pressure or volume are increasing
- W is positive for an expansion whether adiabatic or isothermal
- In a reversible isothermal process, $Q \neq 0$ and the sign of Q is determined by whether volume is increasing or decreasing

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

$Q–W = \Delta E = 0$ since $\Delta T=0$, so $Q = W > 0$

(60) Which one of the following statements is true about the heat transfer in this process?

a. There is no net heat transfer between the gas and its environment.

b. There is net heat transfer to the gas.

c. There is net heat transfer away from the gas.

d. Not enough information.

Correct-response rate

Calculus-based: 43%; Algebra-based: 44%

Q = 0 responses

Calculus-based: 30%; Algebra-based: 37%

You perform an experiment with an ideal monatomic gas such that it undergoes a reversible isothermal compression. Answer questions (4) and (5) below about this experiment.

$Q–W = \Delta E = 0$ since $\Delta T=0$, so $Q = W < 0$

(4) Which one of the following is true about the net heat transfer during the reversible isothermal compression?

a. There is net heat transfer to the gas.

b. There is net heat transfer away from the gas.

c. There is no net heat transfer to or from the gas.

d. Not enough information.

Correct-response rate

Calculus-based: 30%; Algebra-based: 21%

Q = 0 responses

Calculus-based: 50%; Algebra-based: 59%

Many more Q = 0 responses on "reversible compression" question, justified by "process is isothermal" arguments

General Findings

- In problems involving *PV* diagrams, shapes and directions of process arrows often triggered unproductive lines of reasoning regarding work, distracting students from the problem features most relevant to finding a solution.
- Certain terms may by their very presence trigger potentially unproductive lines of reasoning, including, for example, “adiabatic” and “reversible.”
- In thermodynamics, students are prone to focus attention on the “most salient” variable (such as heat in an adiabatic process or work in an isobaric process) while ignoring other crucial variables.

Implications of Findings

- Changes to problem properties considered minor by experts can lead to vastly different correct- (and incorrect-) response rates by students.
- In thermodynamics, certain features of *PV* diagrams or problem wording and terminology can divert students into long chains of confused reasoning regarding work or heat, ignoring the most-relevant problem features.
- In thermodynamics, immediate “intuitive” responses are often linked to a perceived need to carry out lengthy calculations, instead of focusing on problem features that could lead to quick solutions.
- Dual-process theory “process 1” and “process 2” seem to have a propensity to intermingle in the thermodynamics context.