Uneven Development of Students' Reasoning Regarding Concepts in Thermal Physics

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Background

- Previous research on learning of thermal physics:
  - algebra-based introductory physics (Loverude, Kautz, and Heron, 2002)
  - sophomore-level thermal physics (Loverude, Kautz, and Heron, 2002)
  - calculus-based introductory physics (Meltzer, 2004)
- This project:
  - research and curriculum development for upper-level (junior-senior) thermal physics course

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  - ≈ 90% were physics majors or physics/engineering double majors
  - ≈ 90% were juniors or above
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Course taught by DEM using lecture + interactive-engagement

Performance Comparison: Upper-level vs. Introductory Students

- Diagnostic questions given to students in introductory calculus-based course *after* instruction was complete:
  - 1999-2001: 653 students responded to written questions
  - 2002: 32 self-selected, high-performing students participated in one-on-one interviews
- Written pre-test questions given to Thermal Physics students on first day of class

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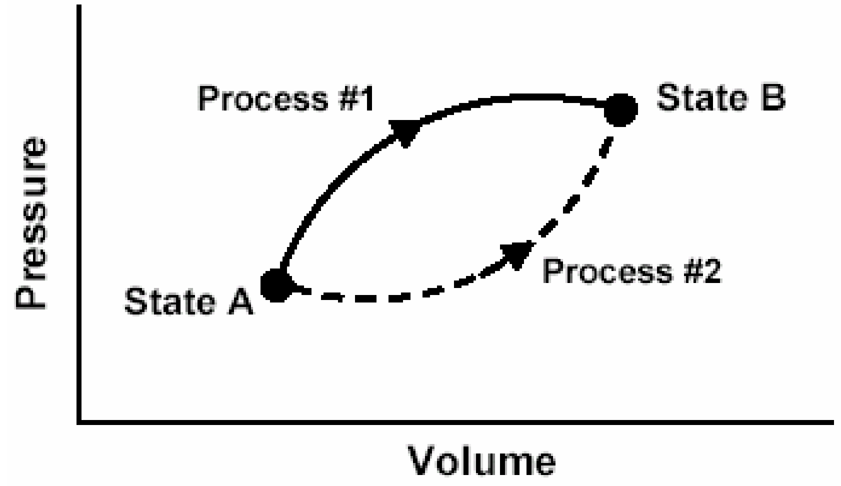

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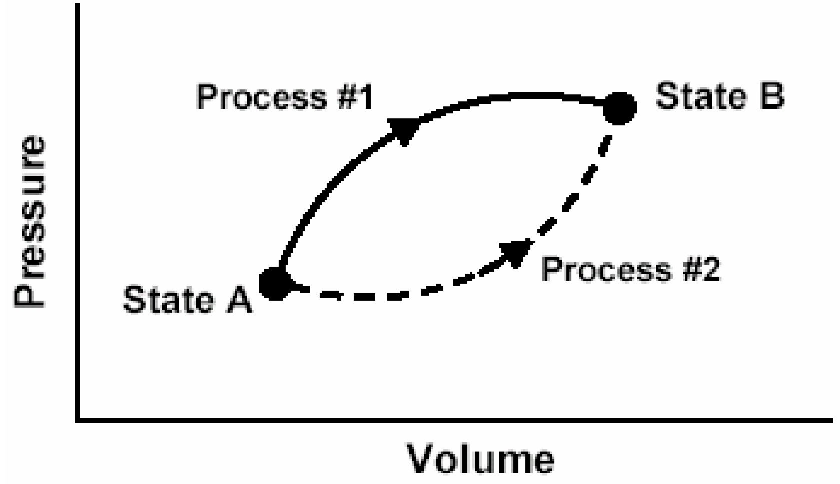

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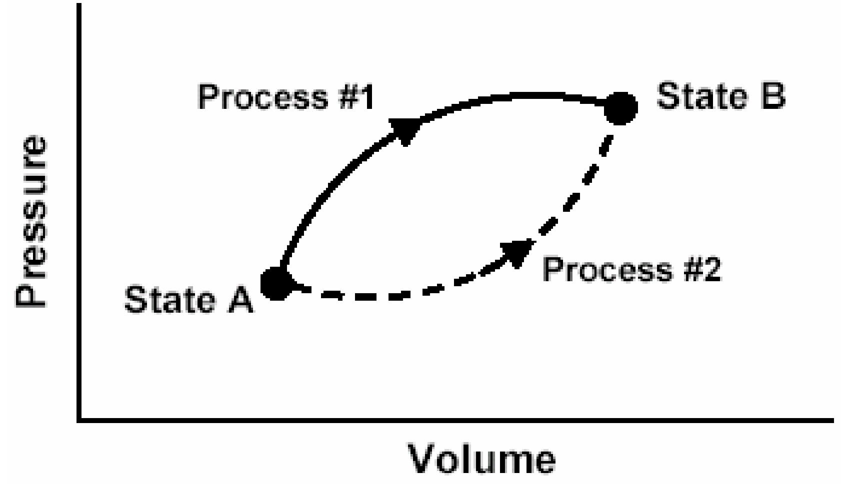

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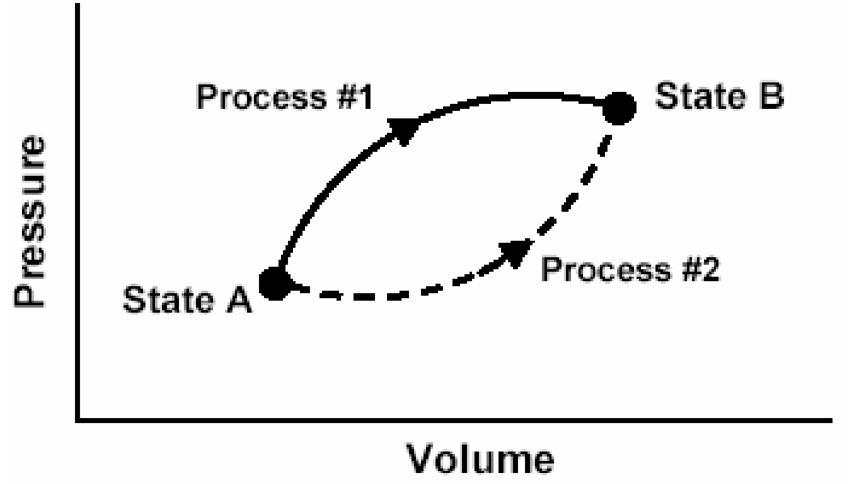
Change in internal energy is the same for Process #1 and Process #2.



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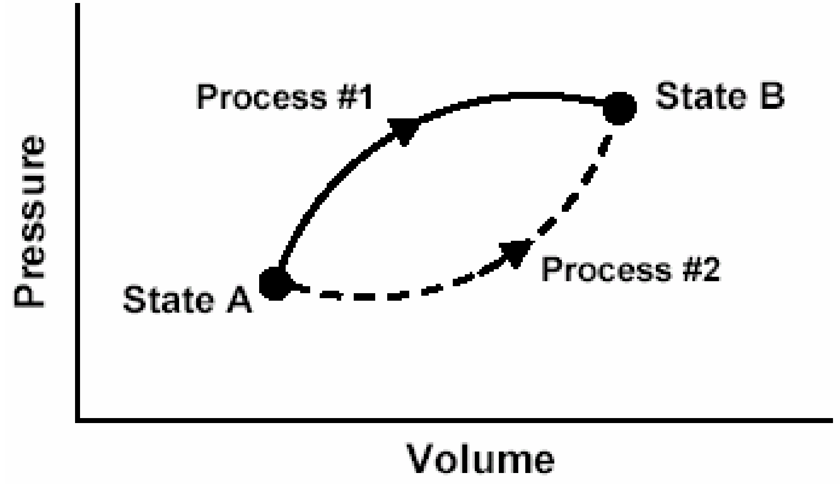
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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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Responses to Diagnostic Question #2
(Heat question)

$Q_1 > Q_2$			

Responses to Diagnostic Question #2
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	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**		
$Q_1 > Q_2$	**45%**		

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

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(Heat question)

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**	**2002** **Introductory Physics** **(Post-test)** **Interview Sample** **(*N*=32)**	**2003** **Thermal Physics** **(Pretest)** **(*N*=14)**
$Q_1 > Q_2$	**45%**	**34%**	**36%**

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(Heat question)

	1999-2001 Introductory Physics (Post-test) Written Sample (N=653)	**2002** Introductory Physics (Post-test) Interview Sample (N=32)	**2003** Thermal Physics (Pretest) (N=14)
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Correct or partially correct explanation	**11%**	**19%**	**29%**

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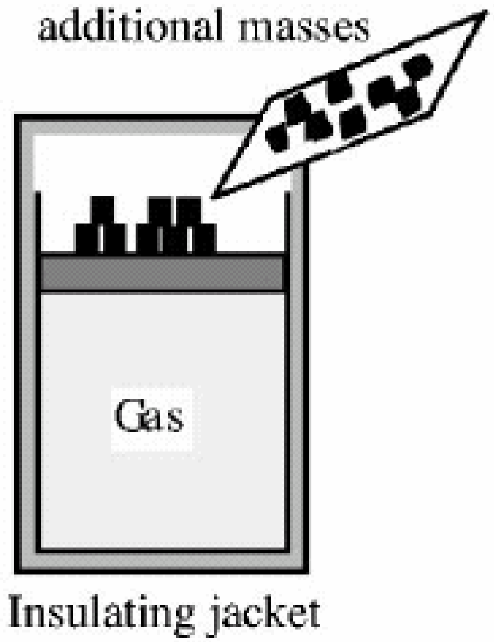
Performance of upper-level students significantly better than introductory students in *written* sample

[*From Loverude, Kautz, and Heron (2002)*]



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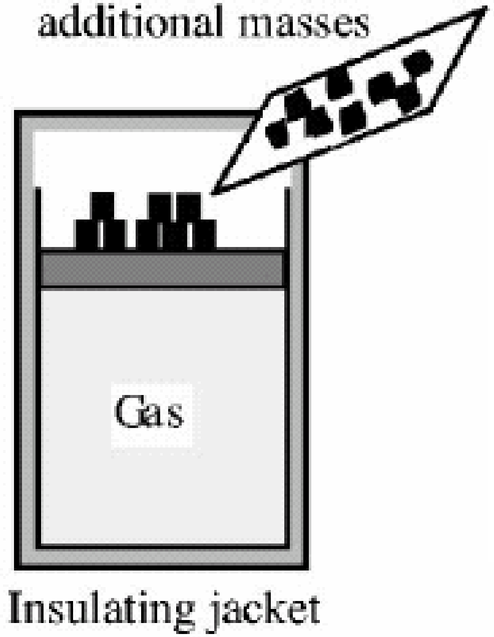

An ideal gas is contained in a cylinder with a tightly fitting piston. Several small masses are on the piston. (See diagram above.)

(Neglect friction between the piston and the cylinder walls.)

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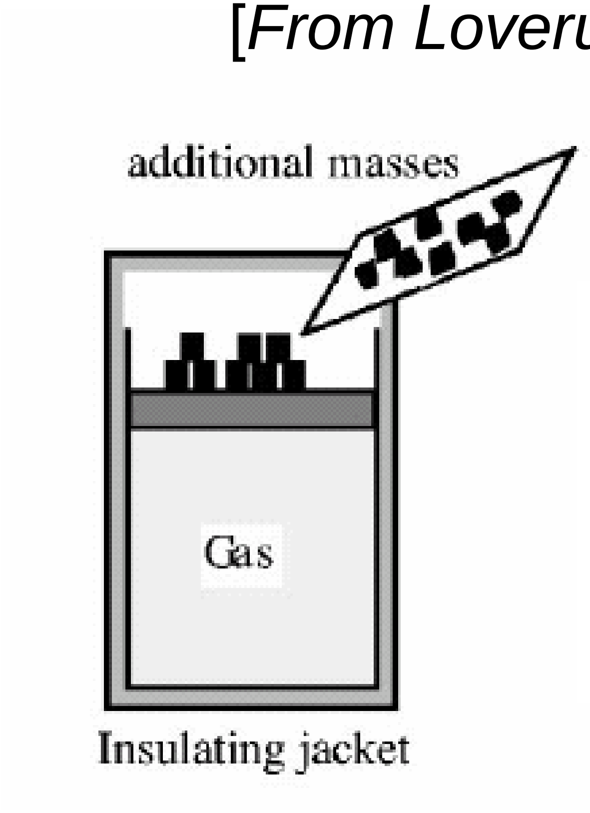

An ideal gas is contained in a cylinder with a tightly fitting piston. Several small masses are on the piston. (See diagram above.)

(Neglect friction between the piston and the cylinder walls.)

The cylinder is placed in an insulating jacket. A large number of masses are added to the piston.

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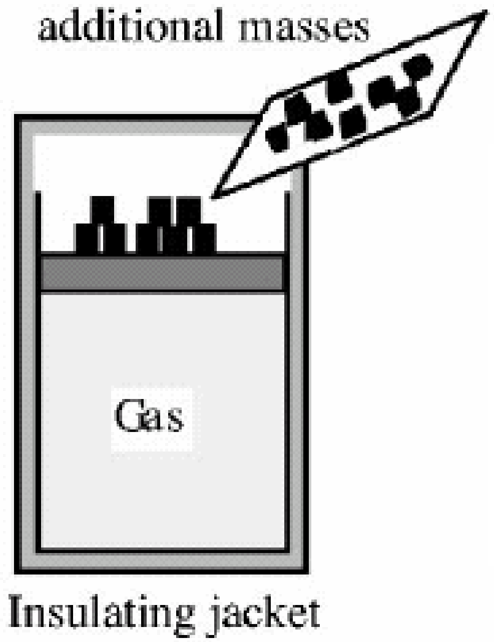

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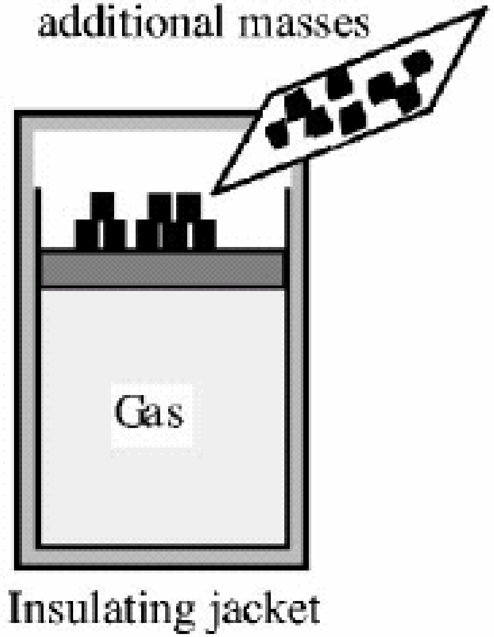
(Neglect friction between the piston and the cylinder walls.)

The cylinder is placed in an insulating jacket. A large number of masses are added to the piston.

Tell whether the pressure, temperature, and volume of the gas will increase, decrease, or remain the same. Explain.



Correct response regarding temperature (2004 student):

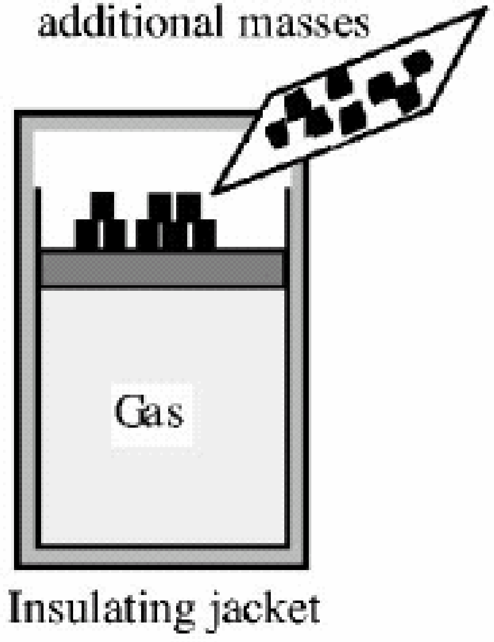
"*I believe the wall will be doing work on the gas thus increasing the kinetic energy of the gas and raising its temperature*."

Thermal Physics (Pre-instruction)

Correct responses regarding temperature:

2003: 21% (N = 14)

2004: 20% (N = 20)



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2003: 21% (N = 14)

2004: 20% (N = 20)

Post-Instruction Results

Final Exam, 2004

$N_{initial} = 20$; $N_{final} = 17$

[one student dropped course, and two others did not show up for final exam (and failed course)]

[University of Maine question]

A system consisting of one mole of a monatomic *ideal gas* goes through three different processes as shown below. The initial values of volume (V_o), pressure (P_o), and temperature (T_o) are the same for each process. Also note that the final volume (V_f) is the same for each process, and that Processes #1 and #2 occur very slowly.

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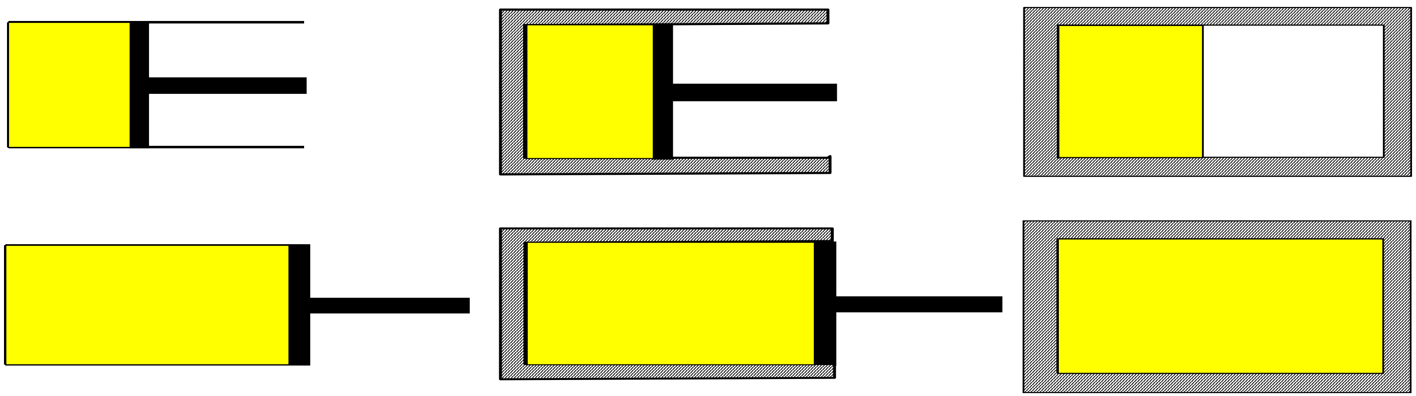

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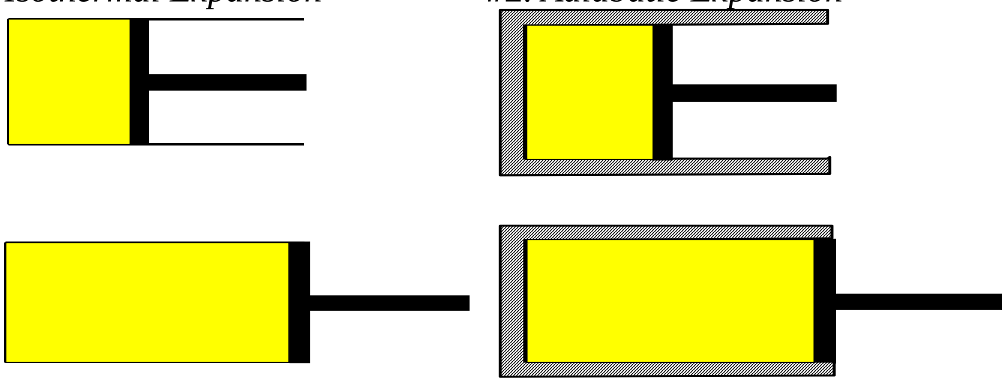

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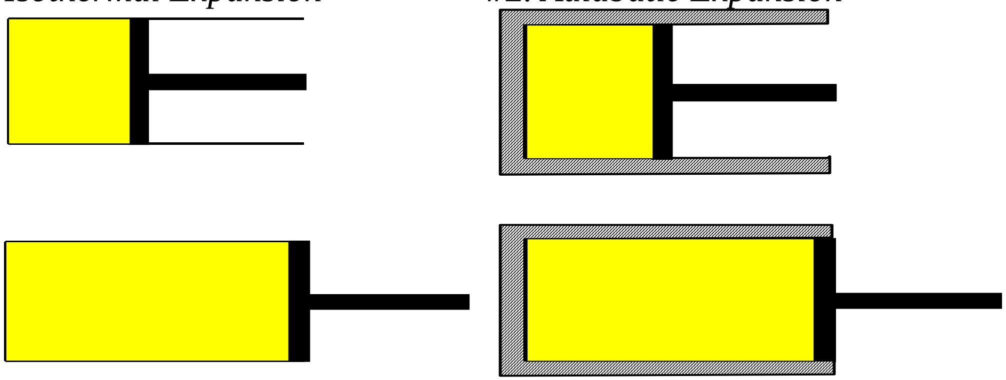

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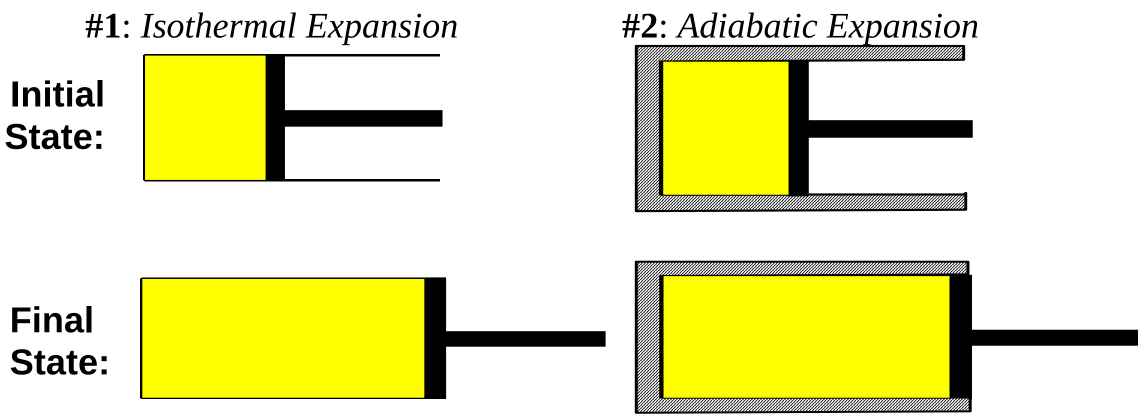

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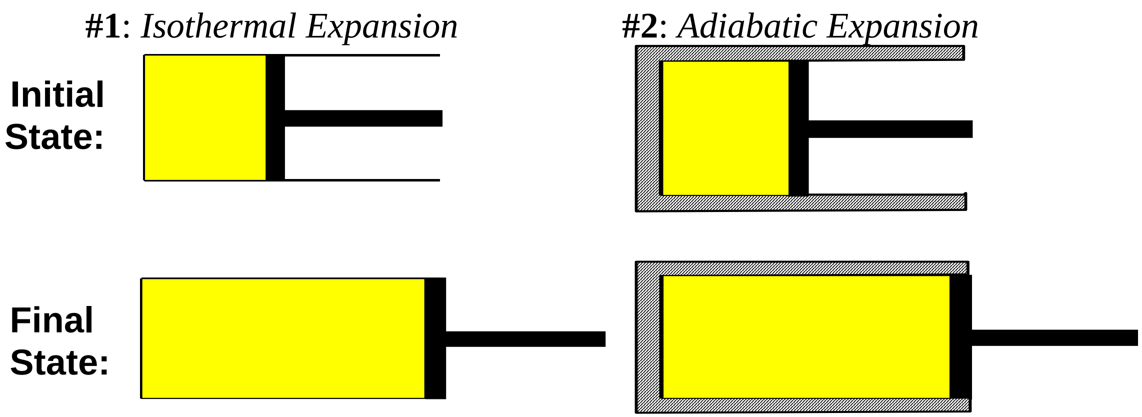

For each of the thermodynamic quantities listed below,

i. ….

ii. *rank* the values of that quantity for each process from greatest to least, …. Explain your answers.

a) ***ΔU***, the change in internal energy, ***W***, the work done *by* the system, ***Q***, the heat transferred *to* the system.

Post-Instruction Results

Final Exam, 2004

$N_{initial}$ = 20; N_{final} = 17

[one student dropped course, and two others did not show up for final exam (and failed course)]

Isothermal process problem and adiabatic process problem:

– All questions regarding *Q*, *W*, and *U* correct:
  - 50% (N = 20); 59% (N = 17)

Only 50% of initial sample finished with good performance on first-law questions

A Special Difficulty: Free Expansion

- Discussed extensively in class in context of entropy’s state-function property
  - group work using worksheets
  - homework assignment
- Poor performance on 2004 final-exam question
  - frequent errors: belief that temperature or internal energy must change, work is done, etc.

Heat Engines and Second-Law Issues

- After extensive study and review of first law of thermodynamics, cyclic processes, Carnot heat engines, efficiencies, etc., students were given pretest regarding various possible (or impossible) versions of two-temperature heat engines.

Consider a system composed of a fixed quantity of gas (not necessarily ideal) that undergoes a cyclic process in which the final state is the same as the initial state.

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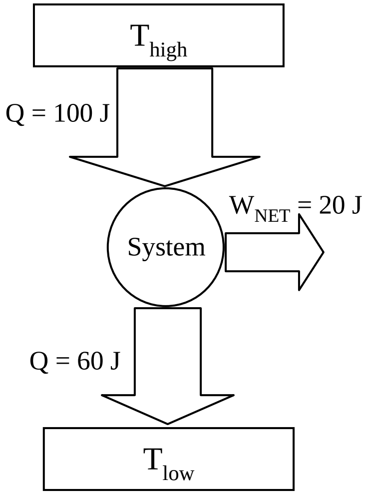
During one particular cyclic process, there is heat transfer to or from the system at only two fixed temperatures: T_{high} and T_{low}

…

For the following processes, state whether they are possible according to the laws of thermodynamics. Justify your reasoning for each question:

heat transfer of 100 J *to* the system at T_{high}
heat transfer of 60 J *away from* the system at T_{low}
net work of 20 J done *by* the system on its surroundings.



(diagram *not* given)

(violation of first law of thermodynamics)

71% correct (*N* = 17)

heat transfer of 100 J *to* the system at T_{high}
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net work of 20 J done *by* the system on its surroundings.

heat transfer of 100 J *to* the system at T_{high}
heat transfer of 0 J *away from* the system at T_{low}
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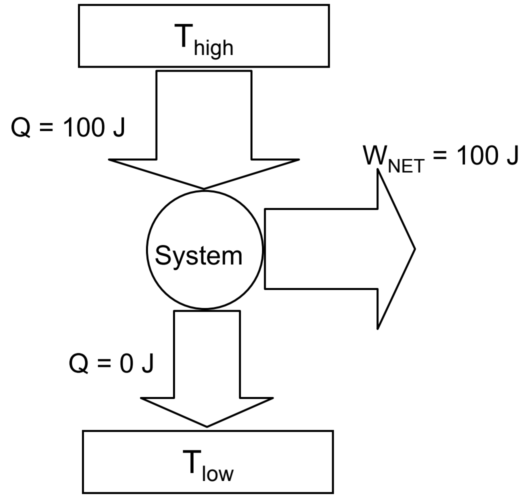

(diagram *not* given)

(Perfect heat engine:
violation of second law of thermodynamics)

59% correct (*N* = 17)

Consistent with results reported by M. Cochran (2002)

Heat Engines: Post-Instruction

- Following extensive instruction on second-law and implications regarding heat engines, graded quiz given as post-test

- Students presented with various cyclic processes at specified temperatures (400 K and 100 K), asked various questions related to them.

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

$$\Rightarrow \eta_{process} = 1 - \frac{|Q_{low-T}|}{Q_{high-T}} = 1 - \frac{100}{300} = 0.67 < \eta_{reversible} = \eta_{max}$$

Process is *possible but irreversible*

53% correct with correct explanation (*N* = 15)

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

At the *end* of the process, is the entropy of the system *larger than*, *smaller than*, or *equal to* its value at the *beginning* of the process?

Answer: $\Delta S_{system} = 0$ since process is cyclic, and S is a state function

40% correct with correct explanation ($N = 15$)

Cycle 1:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 100 J

At the *end* of the process, is the entropy of the system *larger than*, *smaller than*, or *equal to* its value at the *beginning* of the process?

Most common error: Assume $\Delta S_{system} = \sum_i \frac{Q_i}{T_i}$

(forgetting that this equation requires $Q_{reversible}$ and this is *not* a reversible process)

Spontaneous Process Question

[Introductory-Course Version]

3. For each of the following questions consider a system undergoing a naturally occurring ("spontaneous") process. The system can exchange energy with its surroundings.

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

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

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

Responses to Spontaneous Process Question

[Correct Responses]				
S_{system}				
$S_{surroundings}$				
S_{total}				

Responses to Spontaneous Process Question

[Correct Responses]	2004 Introductory Physics (Pretest) (N=289)			
S_{system}				
$S_{surroundings}$				
S_{total}				

Responses to Spontaneous Process Question

[Correct Responses]	2004 Introductory Physics (Pretest) (*N*=289)			
S_{system}	39%			
$S_{surroundings}$	43%			
S_{total}	15%			

Responses to Spontaneous Process Question

[Correct Responses]	2004 Introductory Physics (Pretest) (N=289)	2004 Thermal Physics (Pretest) (N=12)		
S_{system}	39%			
$S_{surroundings}$	43%			
S_{total}	15%			

Responses to Spontaneous Process Question

[Correct Responses]	2004 Introductory Physics (Pretest) (*N*=289)	2004 Thermal Physics (Pretest) (*N*=12)		
S_{system}	39%	50%		
$S_{surroundings}$	43%	50%		
S_{total}	15%	92%		

Responses to Spontaneous Process Question

[Correct Responses]	2004 Introductory Physics (Pretest) (N=289)	2004 Thermal Physics (Pretest) (N=12)	2004 Thermal Physics (Post-Instruction Interviews) (N=12)	
S_{system}	39%	50%		
$S_{surroundings}$	43%	50%		
S_{total}	15%	92%		

Responses to Spontaneous Process Question

[Correct Responses]	2004 Introductory Physics (Pretest) (*N*=289)	2004 Thermal Physics (Pretest) (*N*=12)	2004 Thermal Physics (Post-Instruction Interviews) (*N*=12)	
			correct	
S_{system}	39%	50%	75%	
$S_{surroundings}$	43%	50%	75%	
S_{total}	15%	92%	100%	

Responses to Spontaneous Process Question

[Correct Responses]	2004 Introductory Physics (Pretest) (N=289)	2004 Thermal Physics (Pretest) (N=12)	2004 Thermal Physics (Post-Instruction Interviews) (N=12)	
			correct	with correct explanation
S_{system}	39%	50%	75%	67%
$S_{surroundings}$	43%	50%	75%	75%
S_{total}	15%	92%	100%	100%

Responses to Spontaneous Process Question

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S_{system}	39%	50%	75%	67%
$S_{surroundings}$	43%	50%	75%	75%
S_{total}	15%	92%	100%	100%

Students' Thinking on Spontaneous Processes

- Readily accept that "entropy of universe increases"
  - in contrast to introductory students
- Strong tendency to assume that "system entropy" must *always* increase
- Tendency to *assume* direction of heat flow for "system"
- Difficulty in applying state-function property of entropy (e.g., to analyze irreversible process via reversible process sharing common initial and final states)

Strong similarity to thinking of introductory students

[University of Maine question]

A system consisting of one mole of a monatomic *ideal gas* goes through three different processes as shown below. The initial values of volume (V_o), pressure (P_o), and temperature (T_o) are the same for each process. Also note that the final volume (V_f) is the same for each process, and that Processes #1 and #2 occur very slowly.

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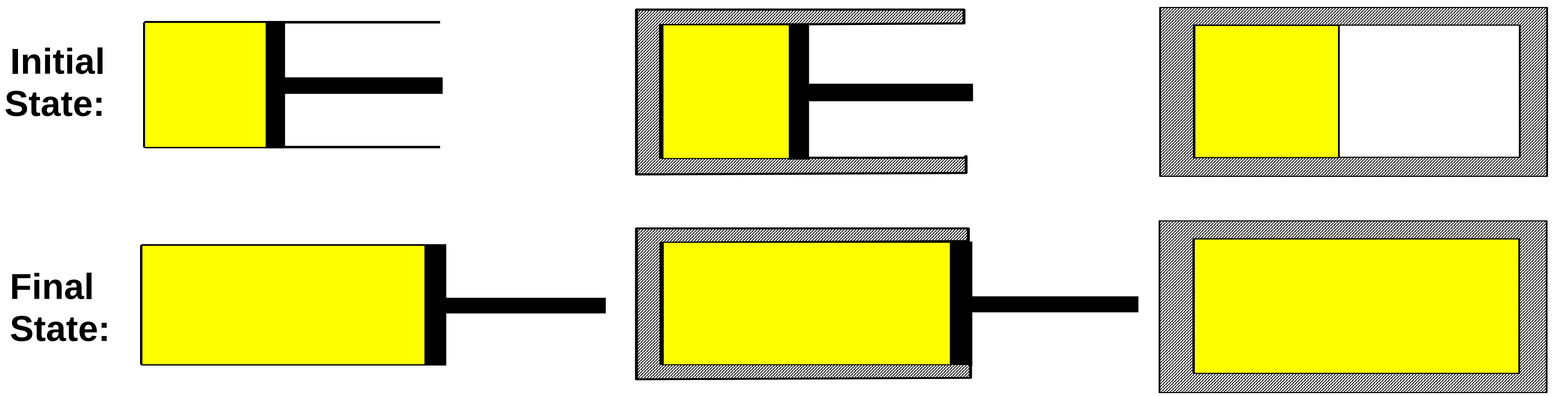

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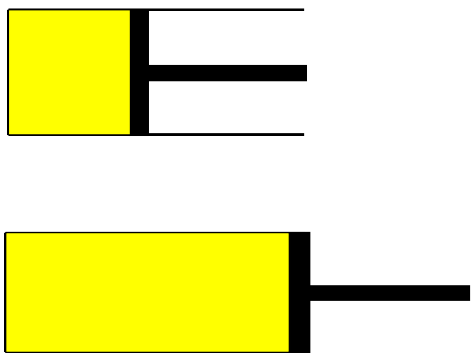
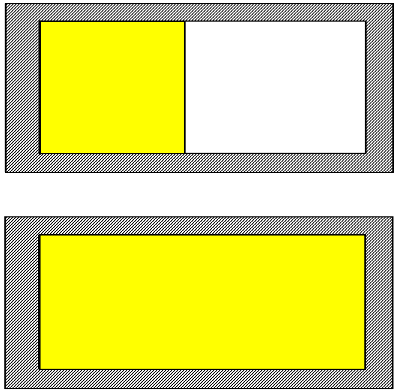
Final State:



#3: *Free Expansion into a Vacuum*



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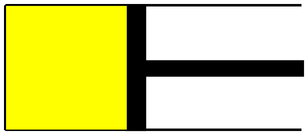
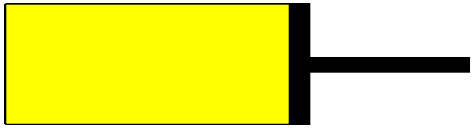
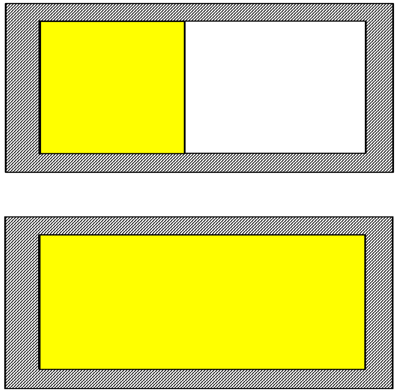


Final State:



#3: *Free Expansion into a Vacuum*



Students were asked to rank magnitudes of Δ*S* for #1 and #3

Example of correct student response:

> "#3: not reversible, but has same initial and final states as #1, so $\Delta S_{sys}(\#3) = \Delta S_{sys}(\#1) > 0$

Results on Free-Expansion Question

- Pre-Instruction (N = 12): 25% correct

  (Similar question, but students *given* that *T* = constant)

- Post-Instruction (N = 12): 50% correct

  $\Delta S_{sys}(\#3) > \Delta S_{sys}(\#1)$: 25%

  $\Delta S_{sys}(\#3) < \Delta S_{sys}(\#1)$: 25%

Difficulties with first-law concepts prevented students from recognizing that T does not change

Summary

- Difficulties with fundamental concepts found among introductory physics students persist for many students beginning upper-level thermal physics course.
- Intensive study incorporating active-learning methods yields only slow progress for many students.