Evolution of Students’ Reasoning Regarding Concepts in Thermal Physics

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Supported in part by NSF DUE #9981140 and PHY-#0406724

Other members of research group

- Ngoc-Loan Nguyen (M.S. 2003, former graduate student)
- Warren Christensen (current Ph.D. student)
- Tom Stroman (new graduate student)

Research on the Teaching and Learning of Thermal Physics

Funded by Physics Division of NSF

- Investigate student learning of statistical thermodynamics
- Probe evolution of students' thinking from introductory through advanced-level course
- Develop research-based curricular materials

In collaboration with John Thompson, University of Maine

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

Course and Students

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  - ≈ 90% were physics majors or physics/engineering double majors
  - ≈ 90% were juniors or above
  - all had studied thermodynamics (some at advanced level)

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Course taught by DEM using lecture + interactive-engagement

Methodological Issues

- Small class sizes imply large year-to-year fluctuations.
- Broad range of preparation and abilities represented among students:
  - very hard to generalize results across sub-groups
- Which students are present or absent for a given diagnostic can significantly influence results.

Threat to Validity: Small Class Size

- Small class sizes imply a relatively high probability that *one* particular class may not be fully representative of students in other, similar classes. [Variance of mean values is relatively large.]

Methodological Challenges

When evaluating students' performance, two distinct factors come into play (hard to distinguish without *extensive* pretesting):

(1) students' knowledge of material previously covered in an introductory course;

(2) students' *learning* of new material during advanced course

Logistical Challenges

- Series of pretests must be administered before material is covered in course
  - too much ground to cover in one-day test
  - cannot be graded for course credit
- Pretests assess knowledge state at particular point in time, but not *readiness to learn*
  - they don't assess rate of knowledge change
  - they don't assess susceptibility to change

Particularly significant (?) in upper-level courses

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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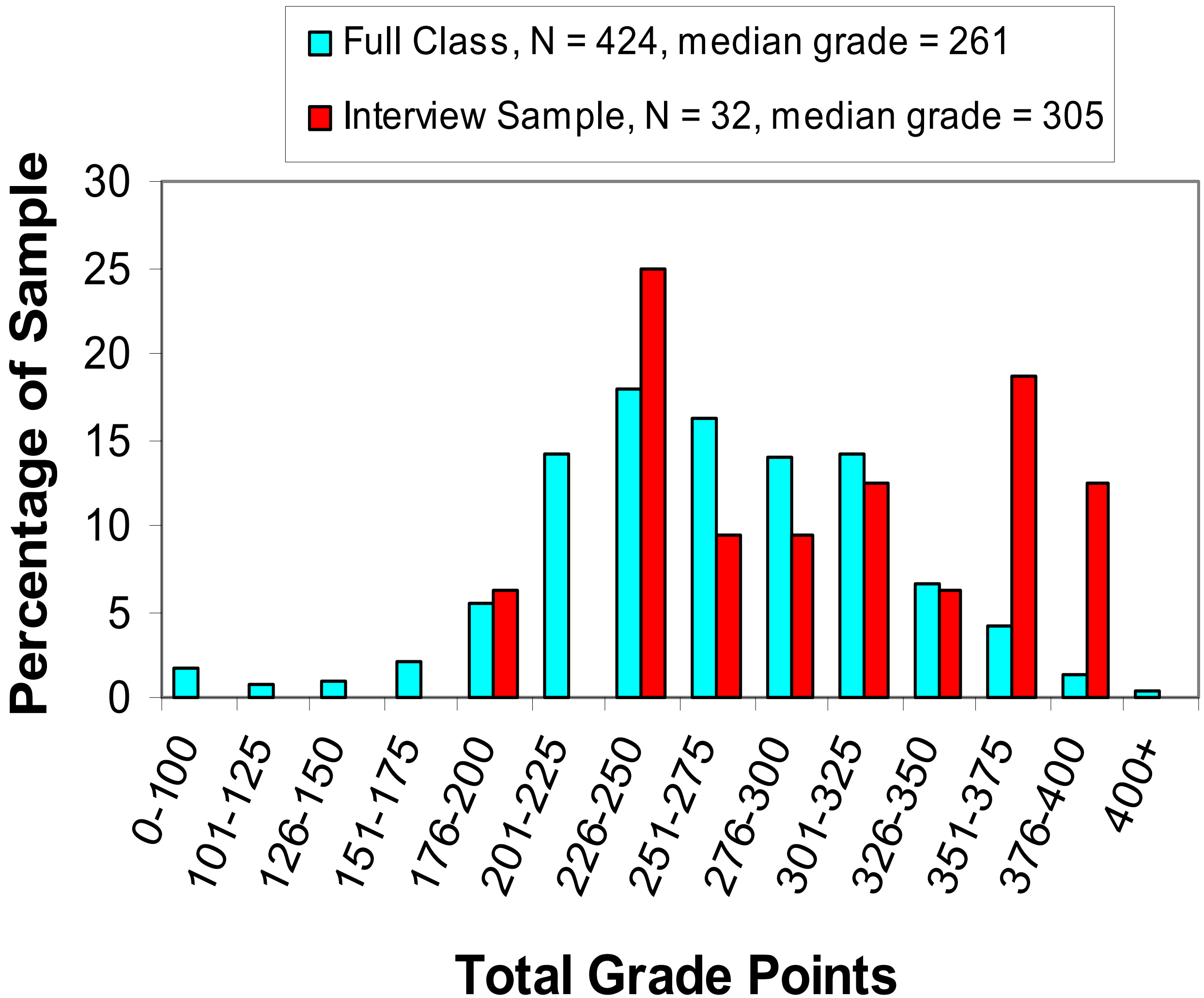
Grade Distributions: Interview Sample vs. Full Class



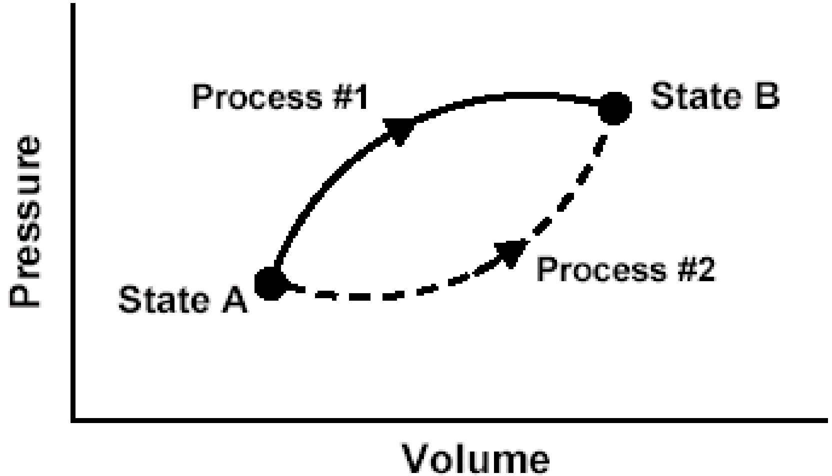
***Interview Sample*:**
34% above 91st percentile; 50% above 81st percentile

Initial Knowledge State

Despite the small size of the upper-level class, wide range of initial knowledge was evident on pretest:

- some students showed good ability to apply first-law concepts, others showed little or none;
- although most students showed at least rudimentary understanding of work and heat, some did not.

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:



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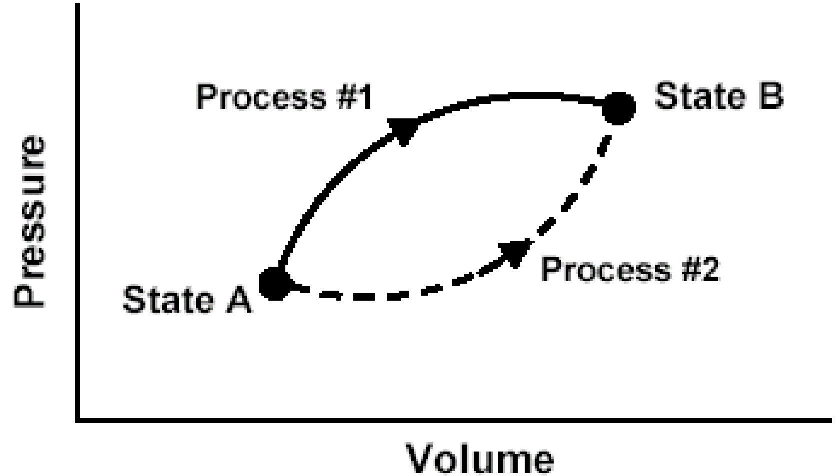

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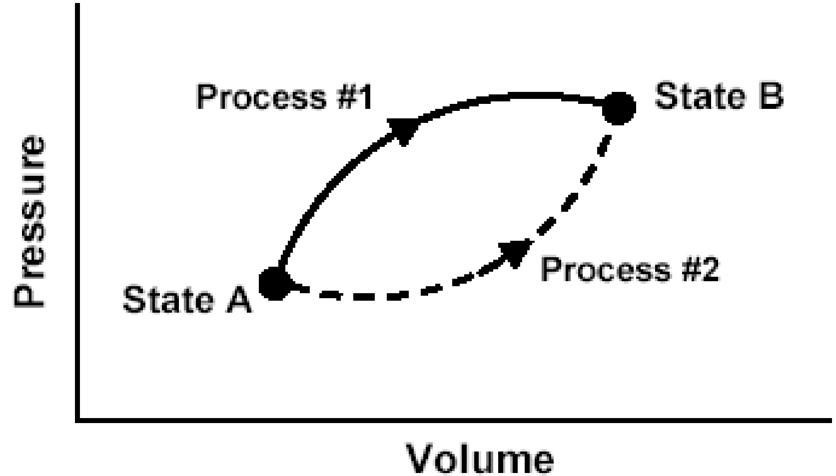

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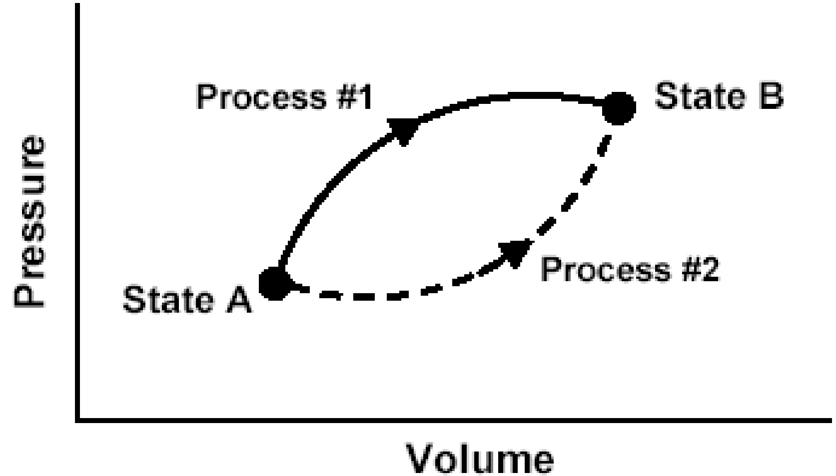

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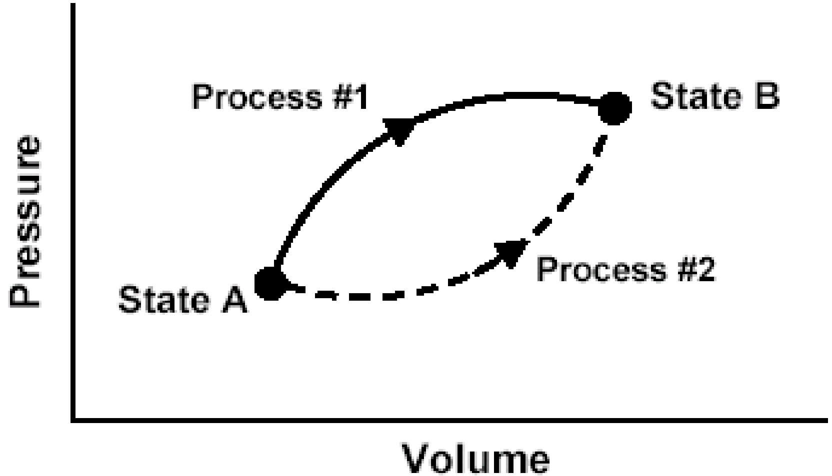

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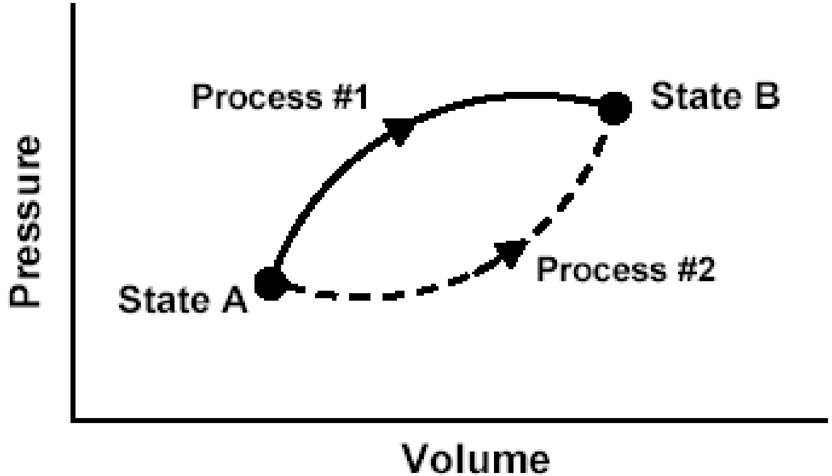

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Responses to Diagnostic Question #1
(Work question)

	1999-2001 Introductory Physics (Post-test) Written Sample (N=653)	**2002** Introductory Physics (Post-test) Interview Sample (N=32)	**2004** Thermal Physics (Pretest) (N=21)
$W_1 > W_2$			
$W_1 = W_2$			
$W_1 < W_2$			

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	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**		
$W_1 = W_2$	**30%**		

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$W_1 = W_2$	**30%**	**22%**	

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$W_1 = W_2$	**30%**	**22%**	**21%**

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About one-quarter of all students believe work done is equal in both processes

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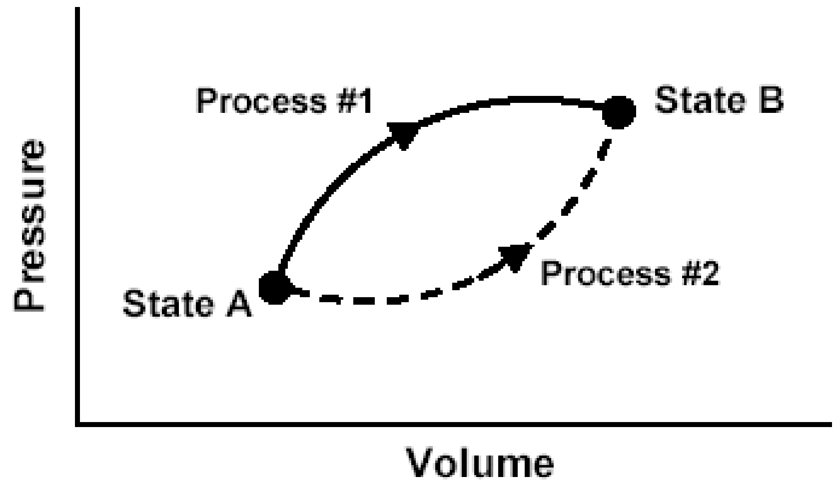

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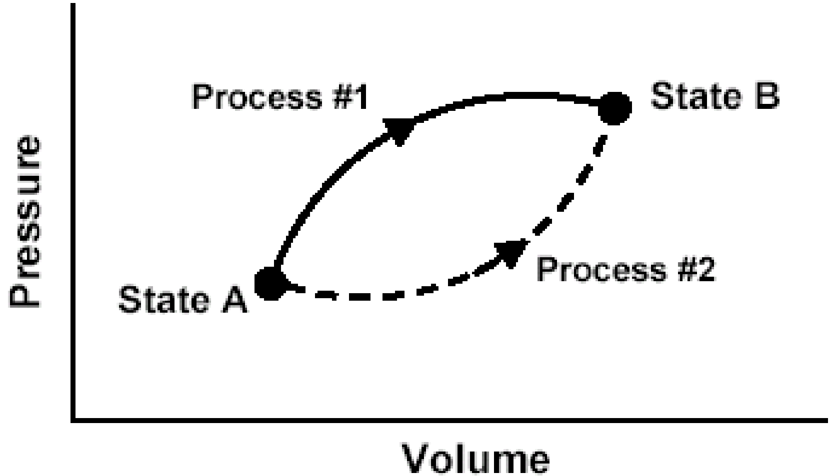

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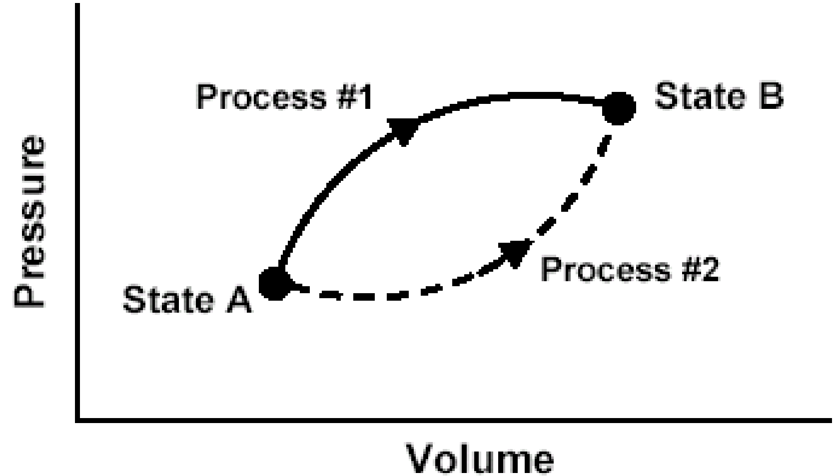
Change in internal energy is the same for Process #1 and Process #2.



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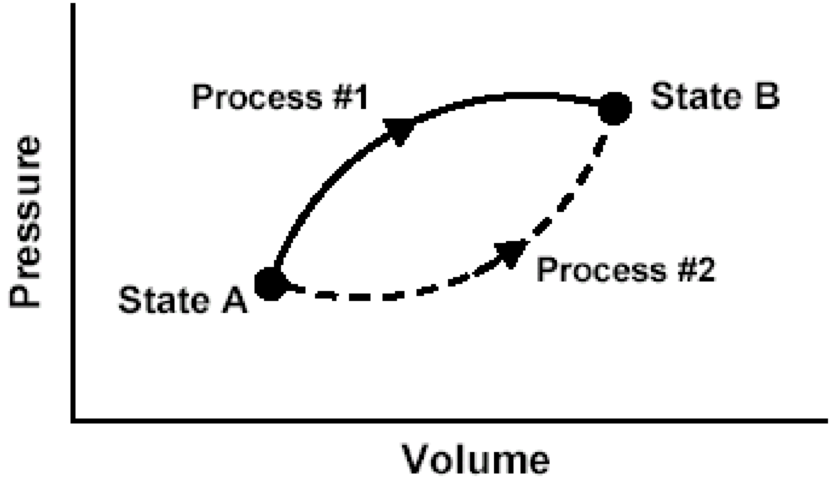
The system does more work in Process #1, so it must absorb more heat to reach same final value of internal energy:
$Q_1 > Q_2$



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Responses to Diagnostic Question #2
(Heat question)

$Q_1 > Q_2$			

Responses to Diagnostic Question #2
(Heat question)

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

Responses to Diagnostic Question #2
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$Q_1 > Q_2$	**45%**	**34%**	

Responses to Diagnostic Question #2
(Heat question)

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$Q_1 > Q_2$	**45%**	**34%**	**36%**

Responses to Diagnostic Question #2
(Heat question)

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$Q_1 > Q_2$	45%	34%	36%
Correct or partially correct explanation	11%	19%	29%

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(Heat question)

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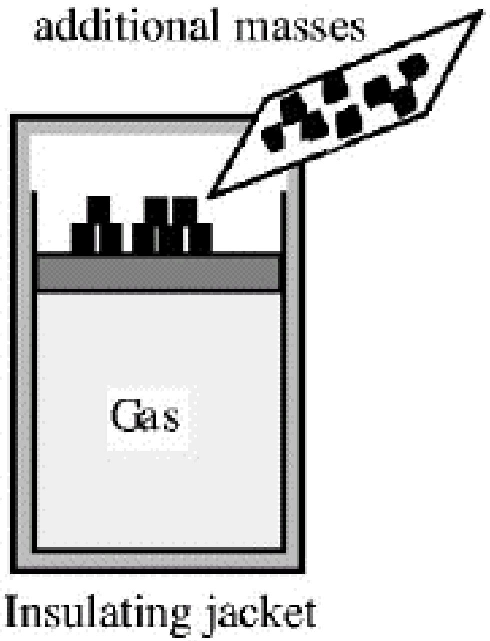
Performance of upper-level students significantly better than introductory students in *written* sample

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



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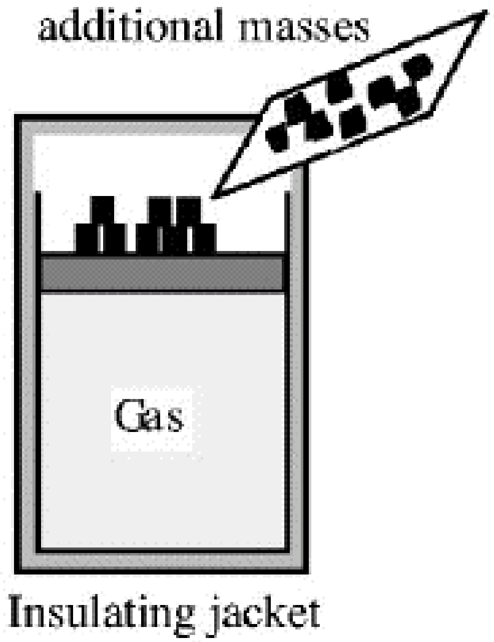

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(Neglect friction between the piston and the cylinder walls.)

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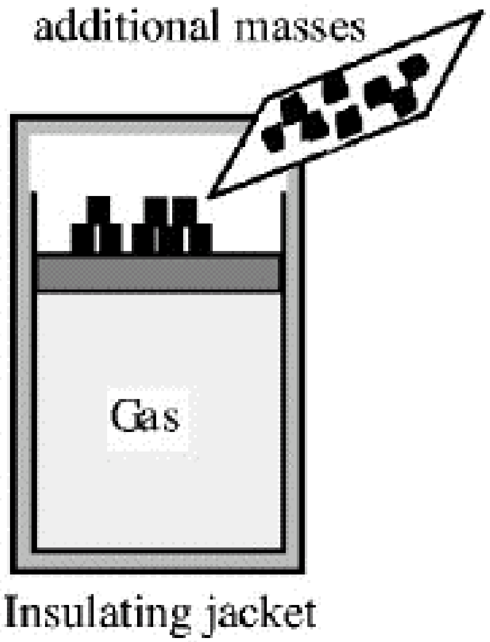

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(Neglect friction between the piston and the cylinder walls.)

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

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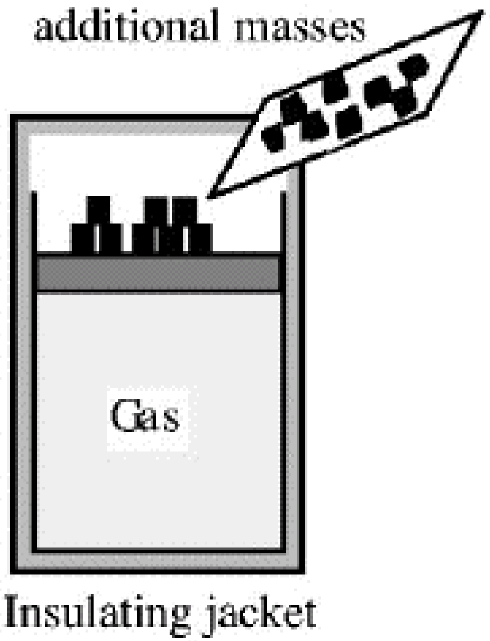

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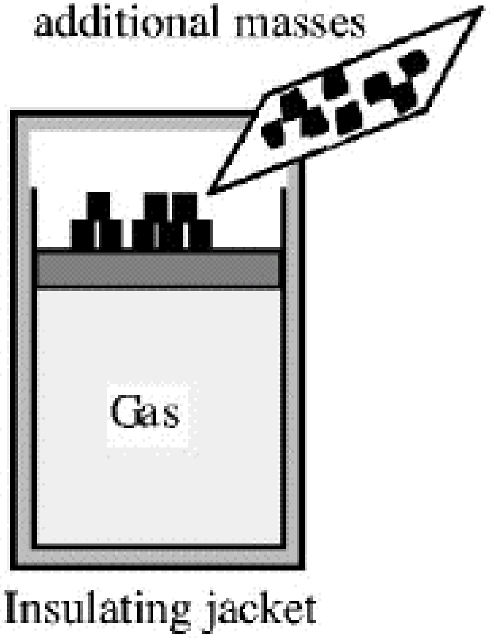
(Neglect friction between the piston and the cylinder walls.)

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):

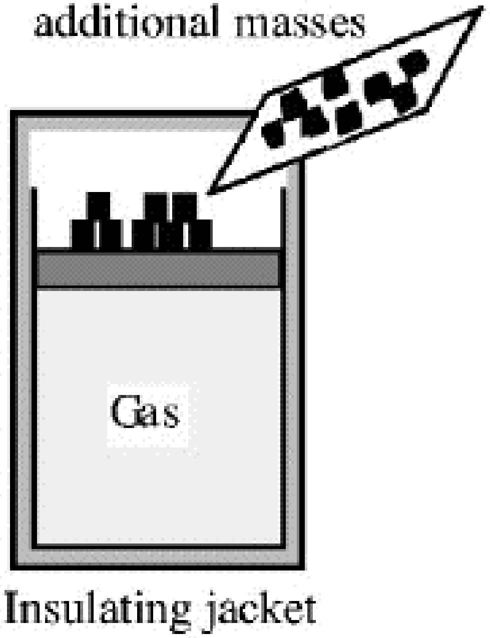
"*I believe the wall will be doing work on the gas thus increasing the kinetic energy of the gas and raising its temperature*."

Thermal Physics (Pre-instruction)

Correct responses regarding temperature:

2003: 21% (N = 14)

2004: 20% (N = 20)



Correct response regarding temperature (2004 student):

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Thermal Physics (Pre-instruction)

Correct responses regarding temperature:

2003: 21% (N = 14)

2004: 20% (N = 20)

Other Comparisons

- Performance of upper-level students on written pretest was not significantly different from interview sample (high-performing introductory students) on post-instruction questions related to:
  - Cyclic processes
  - Isothermal processes
  - Thermal reservoirs

Post-Instruction Results

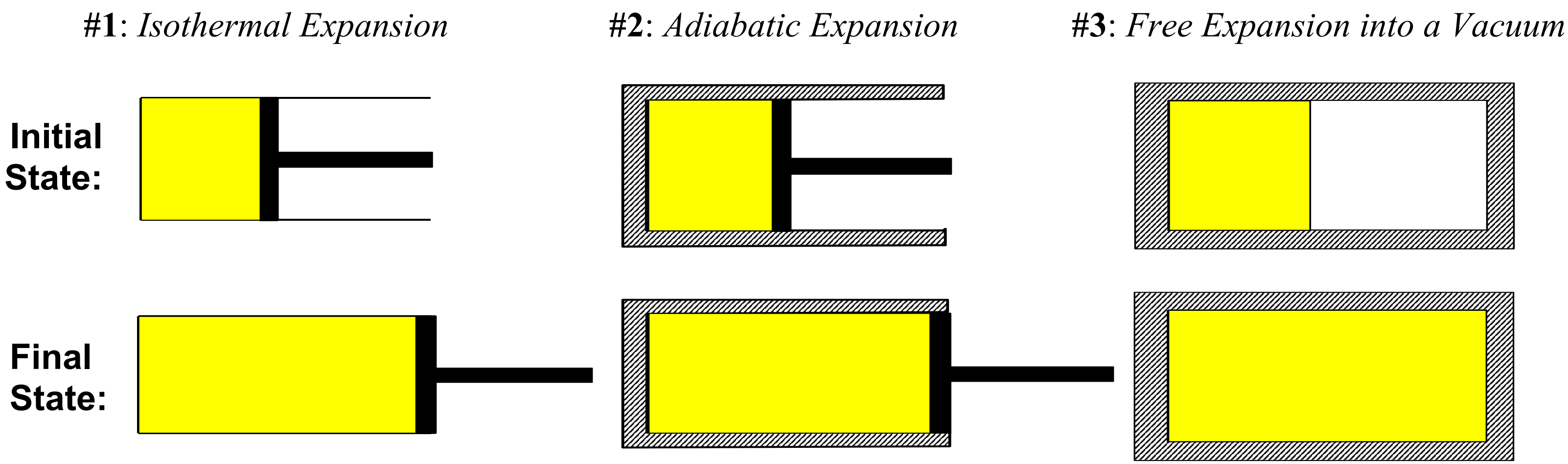
Final Exam, 2004

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

[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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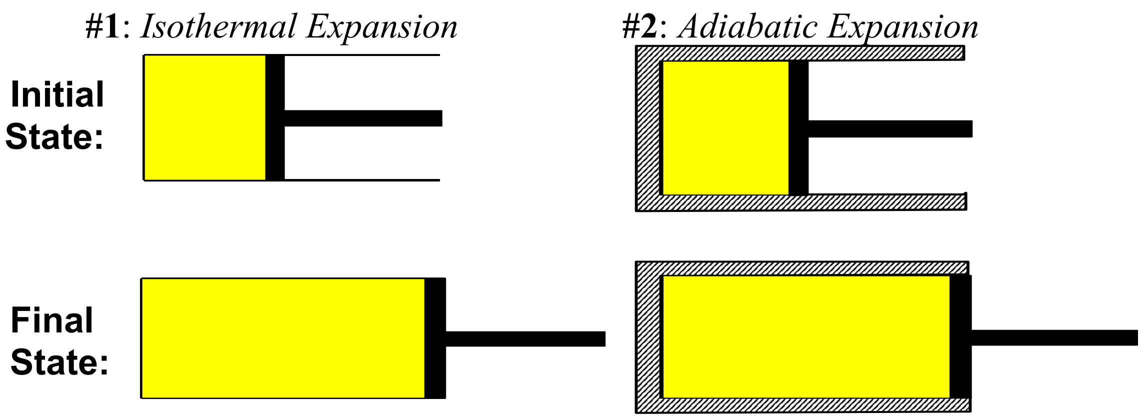

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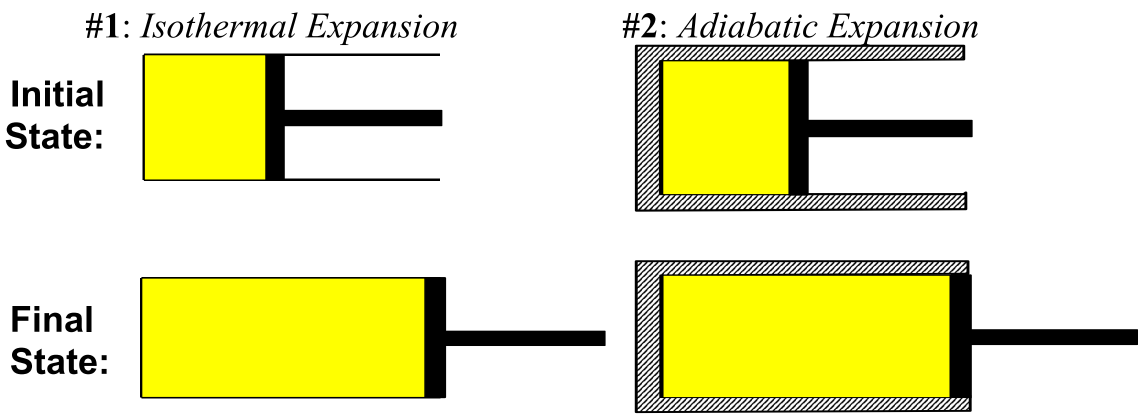

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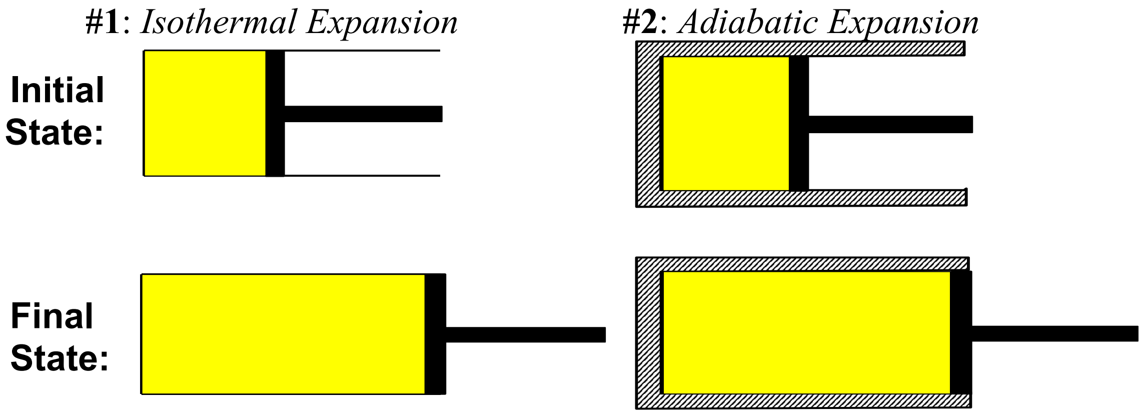

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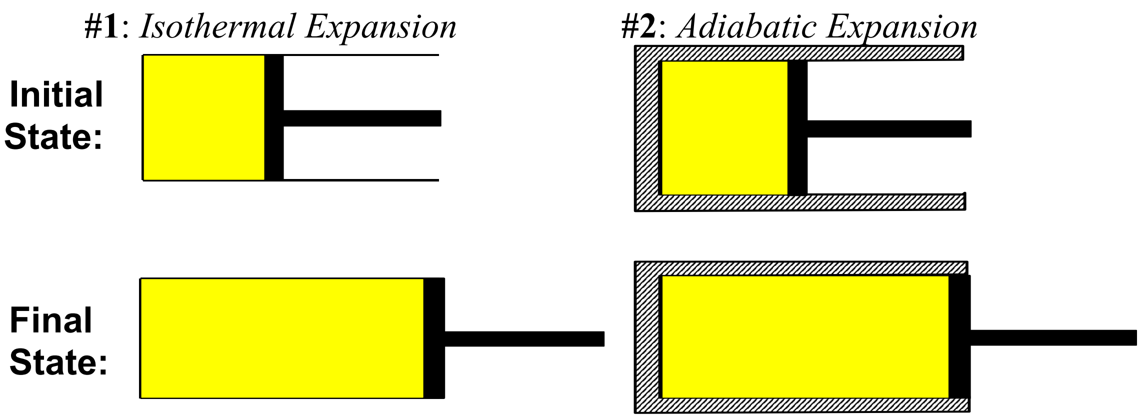

For each of the thermodynamic quantities listed below,

i. specify whether the quantity is *positive, negative,* or *zero* <u>for *each* of the three processes 1, 2 and 3</u>, and briefly *explain* how you know.

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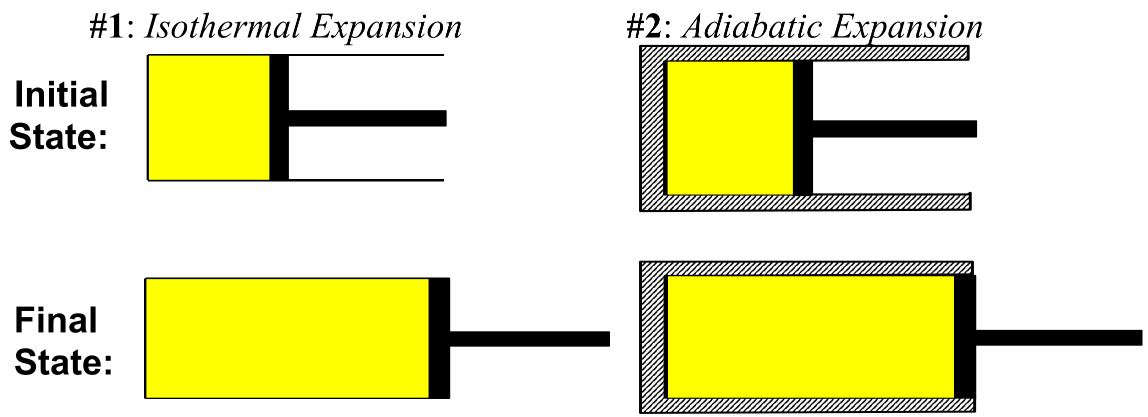

For each of the thermodynamic quantities listed below,

i. specify whether the quantity is *positive, negative,* or *zero* for *each* of the three processes 1, 2 and 3, and briefly *explain* how you know.

ii. *rank* the values of that quantity for each process from greatest to least, keeping in mind that positive values are greater than zero, negative values are less than zero, and a larger negative value is less than a smaller negative value. 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)

– All questions regarding *Q* and *U* correct:
  - 70% (*N* = 20); 82% (*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
  - 40% correct (N = 20), 47% (N = 17) on Q, W, and U questions
  - 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}

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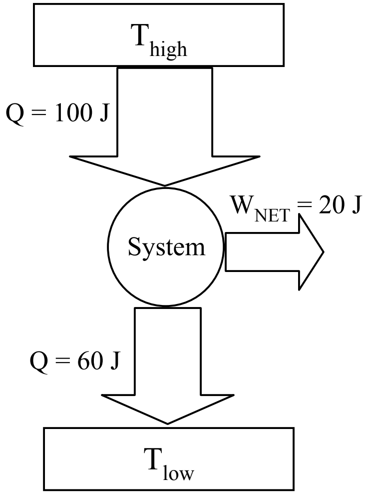
During one particular cyclic process, there is heat transfer to or from the system at only two fixed temperatures: T_{high} and T_{low}

…

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.



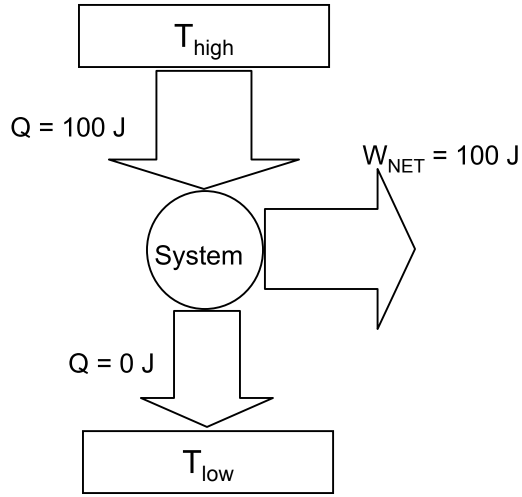
(diagram *not* given)

(violation of first law of thermodynamics)

71% correct (N = 17)

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



(diagram *not* given)

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

59% correct (N = 17)

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

During one particular cyclic process, there is heat transfer to or from the system at only two fixed temperatures: T_{high} and T_{low}. Assume that this process is *reversible*, that is, the process could be reversed by an infinitesimal change in the system properties.

During one particular cyclic process, there is heat transfer to or from the system at only two fixed temperatures: T_{high} and T_{low}. Assume that this process is *reversible*, that is, the process could be reversed by an infinitesimal change in the system properties. Let's also assume that this process has the following properties (where we have specified some particular values for T_{high} and T_{low} such that this process will actually be able to occur):

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 40 J done *by* the system on its surroundings.

During one particular cyclic process, there is heat transfer to or from the system at only two fixed temperatures: T_{high} and T_{low}. Assume that this process is *reversible*, that is, the process could be reversed by an infinitesimal change in the system properties. Let's also assume that this process has the following properties (where we have specified some particular values for T_{high} and T_{low} such that this process will actually be able to occur):

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 40 J done *by* the system on its surroundings.

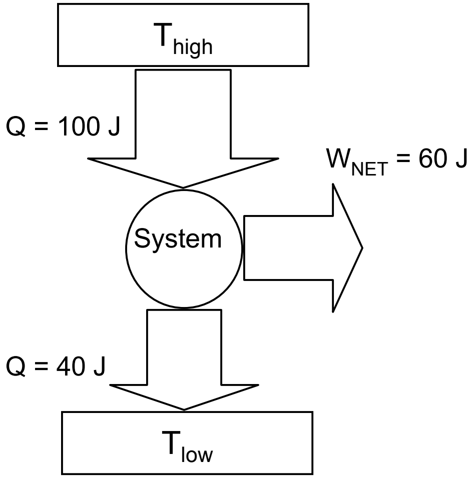
$$\Rightarrow \eta_{reversible} = \frac{W}{Q_{in}} = \frac{40}{100} = 0.40 = \eta_{max}$$

← *Not* given

Now consider a set of processes in which T_{high} and T_{low} have *exactly the same numerical values* as in the example above, but these processes are *not* necessarily reversible.

Now consider a set of processes in which T_{high} and T_{low} have *exactly the same numerical values* as in the example above, but these processes are *not* necessarily reversible. For the following process, state whether it is 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 40 J *away from* the system at T_{low}
net work of 60 J done *by* the system on its surroundings.



(diagram *not* given)

$$\Rightarrow \eta_{process} = \frac{W}{Q_{in}} = \frac{60}{100} = 0.60 > \eta_{reversible}$$ (violation of second law)

0% correct (*N* = 15)

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

Consider the following cyclic processes which are being evaluated for possible use as heat engines.

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For each process, there is heat transfer *to* the system at T = 400 K, and heat transfer *away from* the system at T = 100 K. There is no heat transfer at any other temperatures.

Consider the following cyclic processes which are being evaluated for possible use as heat engines.

For each process, there is heat transfer *to* the system at T = 400 K, and heat transfer *away from* the system at T = 100 K. There is no heat transfer at any other temperatures.

For each cyclic process, answer the following questions: Is the process a *reversible* process, a process that is *possible but irreversible*, or a process that is *impossible*? Explain. (You might want to consider efficiencies.)

$$\Rightarrow \eta_{Carnot} = 1 - \frac{T_{low}}{T_{high}} = 1 - \frac{100}{400} = 0.75 = \eta_{reversible} = \eta_{max}$$

← *Not* given

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

Cycle 2:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

Cycle 3:
heat transfer at high temperature is 200 J;
heat transfer at low temperature is 50 J

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

Cycle 2:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

Cycle 3:
heat transfer at high temperature is 200 J;
heat transfer at low temperature is 50 J

Cycle 2:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

$$\eta_{process} = \frac{W}{Q_{in}}$$

$$\eta_{process} = \frac{W}{Q_{in}} = \frac{Q_{in} - |Q_{out}|}{Q_{in}} = 1 - \frac{|Q_{out}|}{Q_{in}}$$

$$= 1 - \frac{|Q_{low-T}|}{Q_{high-T}}$$

Cycle 2:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

$$\Rightarrow \eta_{process} = 1 - \frac{|Q_{low-T}|}{Q_{high-T}} = 1 - \frac{60}{300} = 0.80 > \eta_{reversible} = \eta_{max}$$

Process is *impossible*

60% correct with correct explanation (*N* = 15)

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

Cycle 2:
heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

Cycle 3:
heat transfer at high temperature is 200 J;
heat transfer at low temperature is 50 J

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]	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%	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*=17)	
			correct	
S_{system}	39%	50%	76%	
$S_{surroundings}$	43%	50%	88%	
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=17)	
			correct	with correct explanation
S_{system}	39%	50%	76%	47%
$S_{surroundings}$	43%	50%	88%	76%
S_{total}	15%	92%	100%	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*=17)	
			correct	with correct explanation
S_{system}	39%	50%	76%	47%
$S_{surroundings}$	43%	50%	88%	76%
S_{total}	15%	92%	100%	100%

Challenges and Difficulties

- Both highly favorable and highly unfavorable reactions toward interactive-engagement techniques were displayed by upper-level students.
  - 10-15% unfavorable rating on evaluations matched that found in introductory algebra-based course.
- Use of guided-inquiry worksheets during class (instead of in separate recitation section) created logistical difficulties due to broad range of speeds with which students worked.

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.
- Large variations in performance among different students persist throughout course.