Development of Student Reasoning in an Upper-Level Thermal Physics Course

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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
  - in collaboration with John Thompson, University of Maine

Course and Students

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  - all but one were juniors or above
  - all had studied thermodynamics
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Course taught by DEM using lecture + interactive-engagement

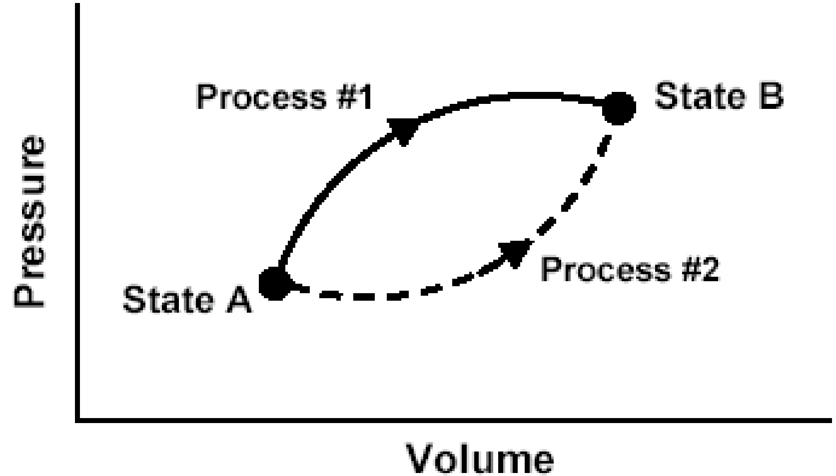
Methodological Issues

- Small class sizes imply large year-to-year fluctuations.
- Broad range of preparation and abilities represented among students:
  - (roughly 1/3, 1/3, 1/3, “high,” “medium,” “low”)
  - very hard to generalize results across sub-groups
- Which students are present or absent for a given diagnostic can significantly influence results.

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

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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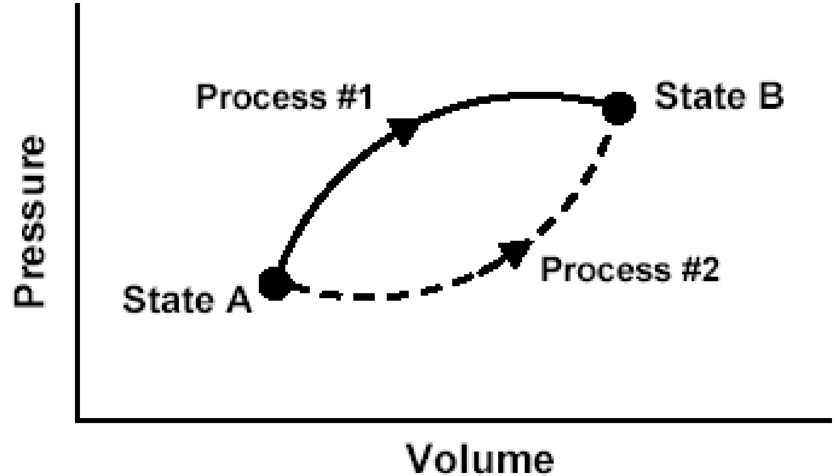

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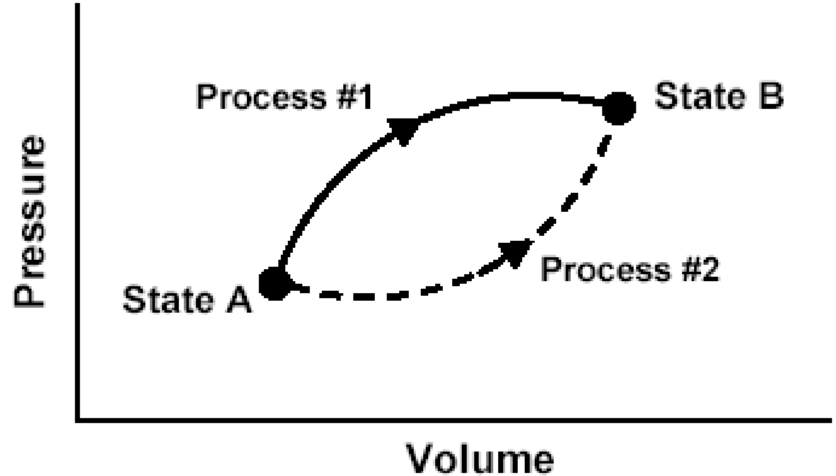

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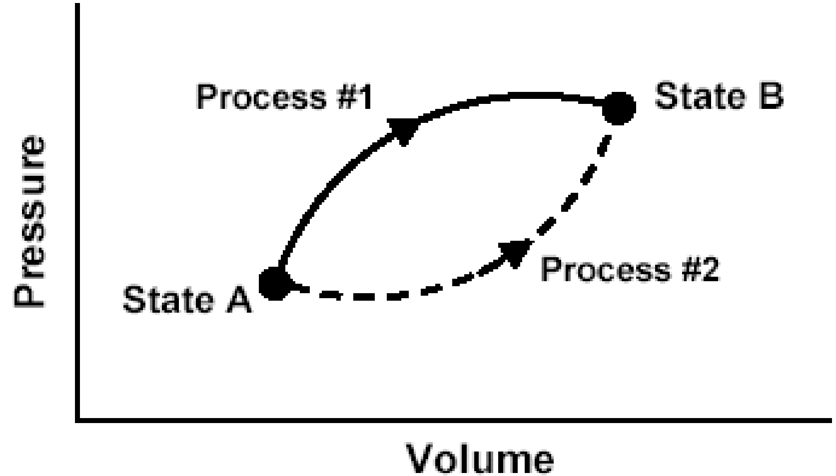

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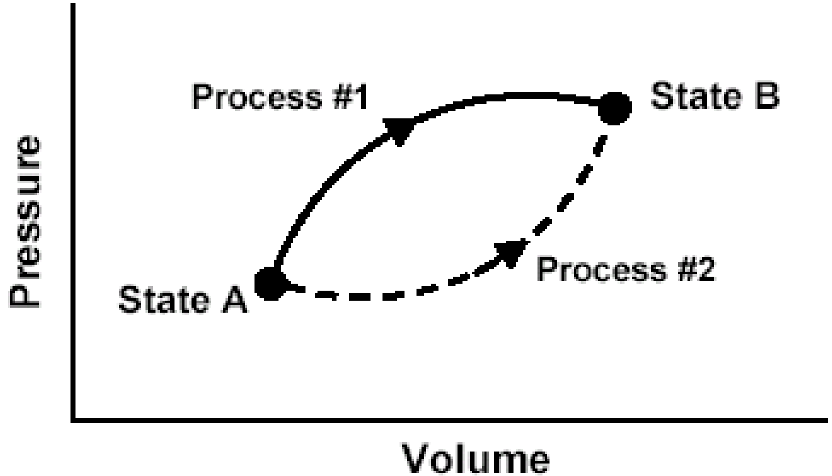

$$W_1 > W_2$$

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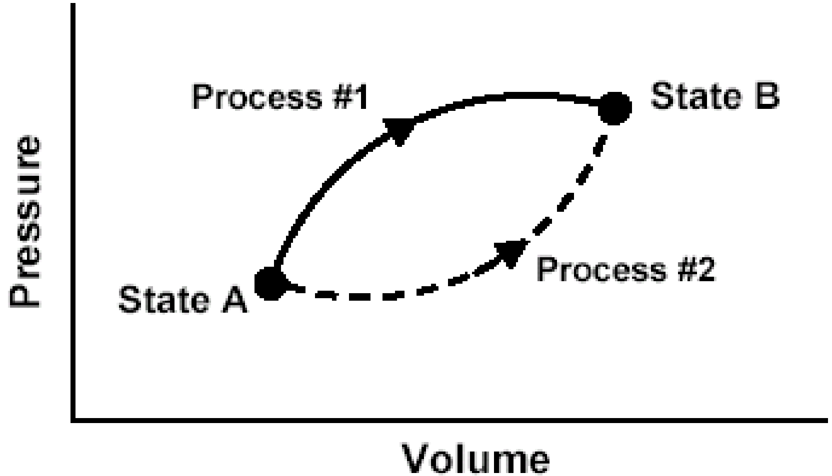

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Responses to Diagnostic Question #1
(Work question)

	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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$W_1 = W_2$	**30%**		

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

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$W_1 = W_2$	**30%**	**22%**	**24%**

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

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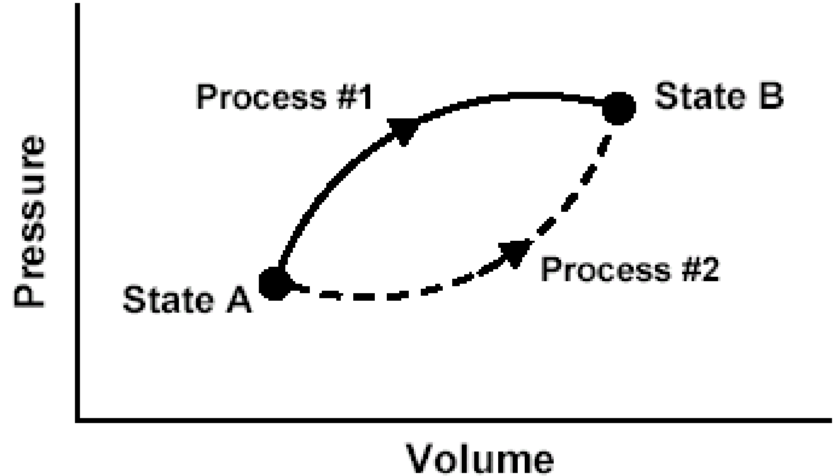

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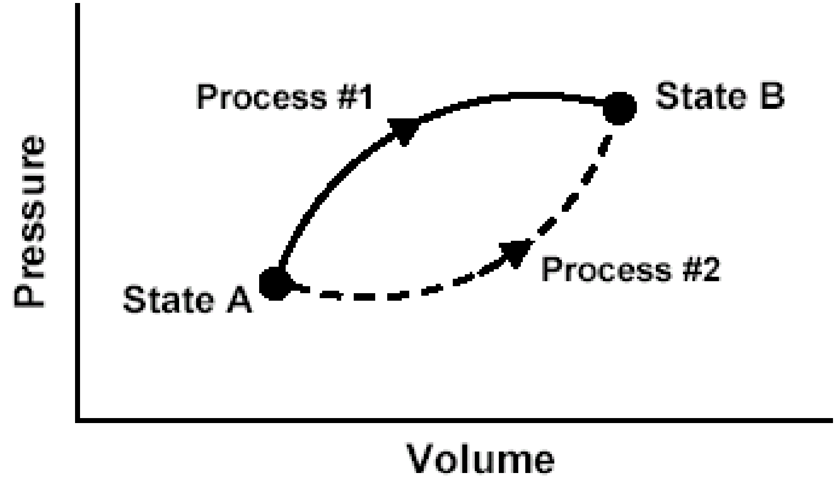

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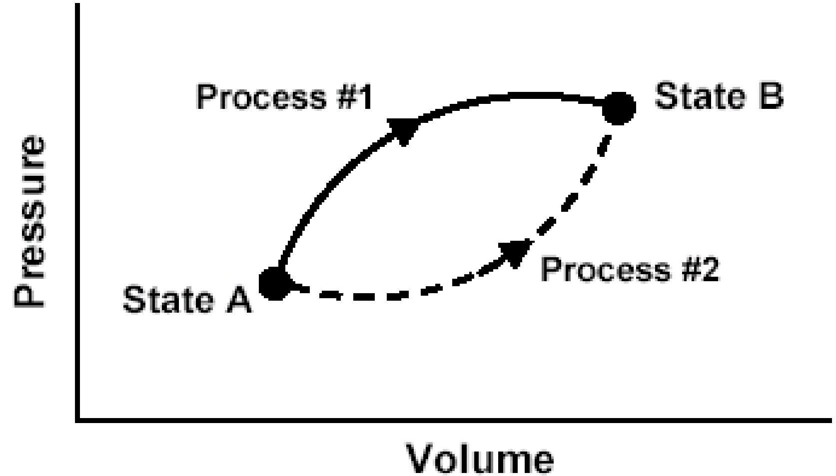
Change in internal energy is the same for Process #1 and Process #2.



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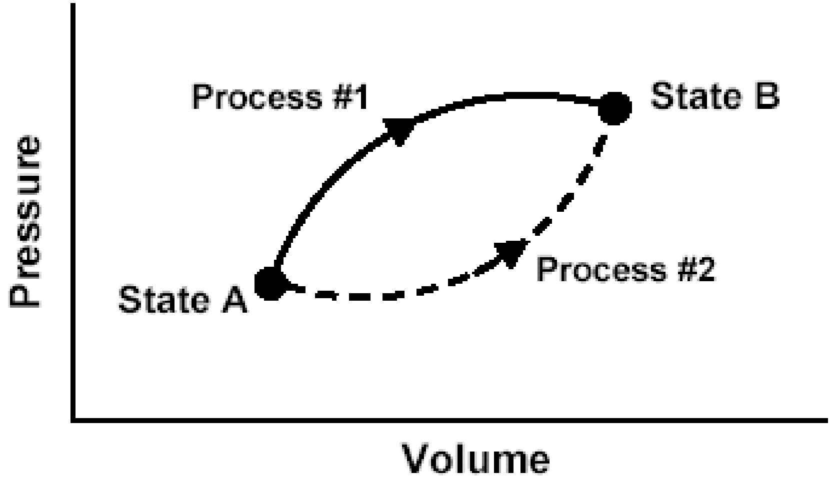
The system does more work in Process #1, so it must absorb more heat to reach same final value of internal energy:
$Q_1 > Q_2$



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Responses to Diagnostic Question #2
(Heat question)

$Q_1 > Q_2$			

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

Responses to Diagnostic Question #2
(Heat question)

	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%**	

Responses to Diagnostic Question #2
(Heat 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)
$Q_1 > Q_2$	**45%**	**34%**	**33%**

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(Heat question)

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$Q_1 > Q_2$	**45%**	**34%**	**33%**
Correct or partially correct explanation	**11%**	**19%**	**33%**

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

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

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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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.

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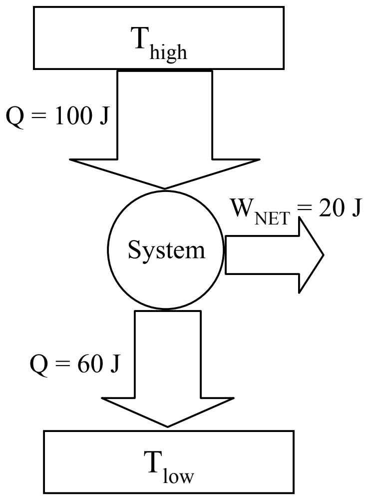

(diagram *not* given)

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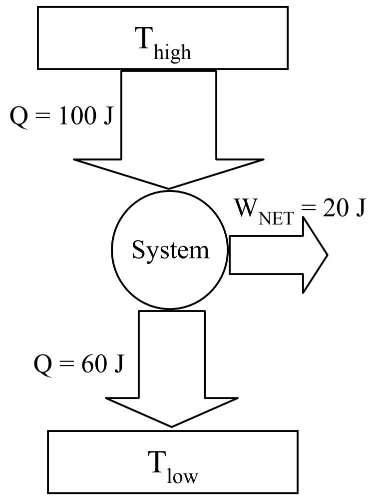
net work of 20 J done *by* the system on its surroundings.



(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.

heat transfer of 100 J *to* the system at T_{high}
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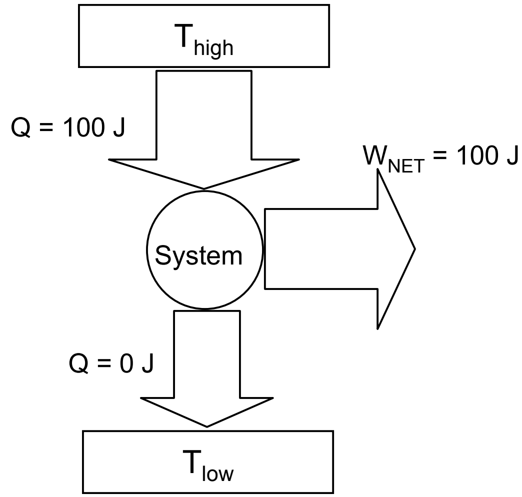

(diagram *not* given)

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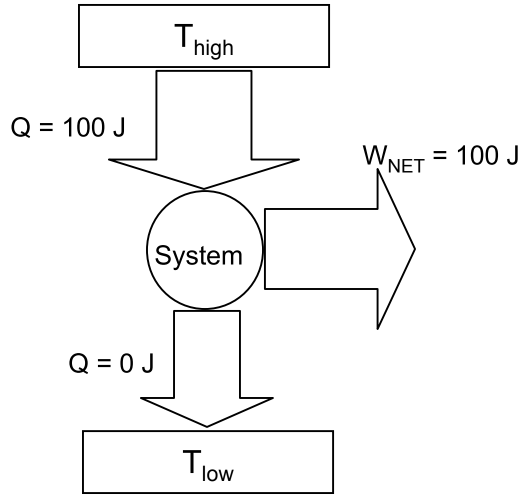
net work of 100 J done *by* the system on its surroundings.



(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}.

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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):

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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.

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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.

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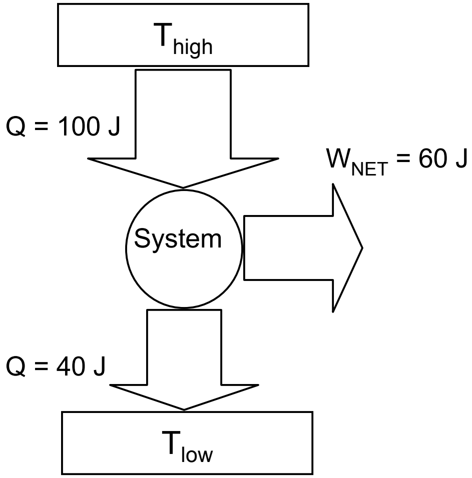

(diagram *not* given)

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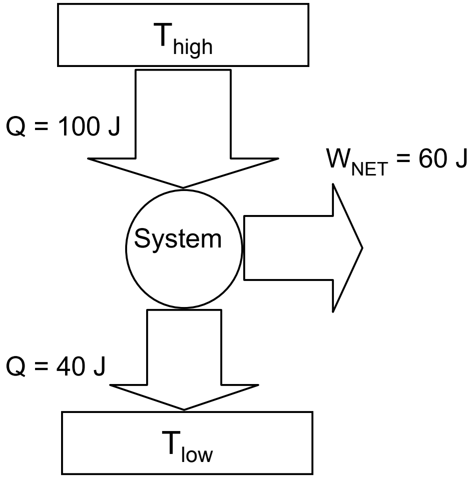

(diagram *not* given)

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

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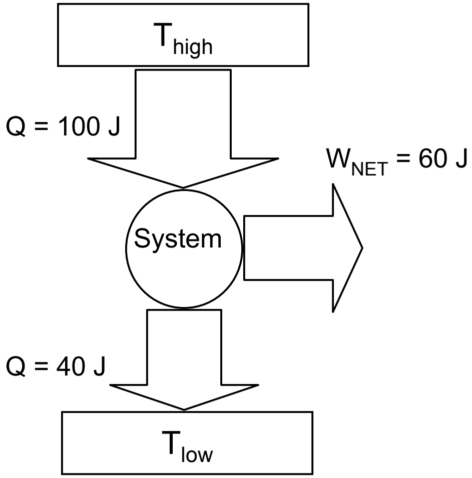

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0% correct (N = 15)

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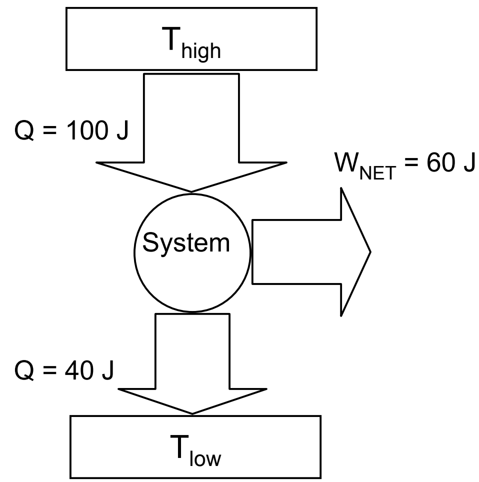

(diagram *not* given)

$$\Rightarrow \eta_{process} = \frac{W}{Q_{in}} = \frac{60}{100} = 0.60 > \eta_{reversible}$$ (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.

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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.

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.)

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

← *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

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heat transfer at high temperature is 300 J;
heat transfer at low temperature is 60 J

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

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*

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

Cycle 1:
heat transfer at high temperature is 300 J;
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$$\Rightarrow \eta_{process} = 1 - \frac{|Q_{low-T}|}{Q_{high-T}} = 1 - \frac{100}{300} = 0.67 < \eta_{reversible} = \eta_{max}$$

Process is *possible but irreversible*

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

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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)

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.