Students' Reasoning Regarding Entropy and the Second Law of Thermodynamics in an Upper-Level Thermal Physics Course

David E. Meltzer and Warren M. Christensen

Department of Physics and Astronomy

Iowa State University

Ames, Iowa

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

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

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

Course and Students

- **Topics:** Approximately equal balance between classical macroscopic thermodynamics, and statistical thermodynamics (Texts: Sears and Salinger; Schroeder)

- **Students enrolled, 2004** ($N_{initial}$ = 20):
  - all but three were physics majors or physics/engineering double majors
  - all but one were juniors or above
  - all had studied thermodynamics

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

[Intro course data: DEM, Am. J. Phys. ***72****, 1432 (2004)]*

Responses to Question Requiring Use of First Law of Thermodynamics

Responses to Question Requiring Use of First Law of Thermodynamics

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**		

Responses to Question Requiring Use of First Law of Thermodynamics

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**		
Correct	**45%**		

Responses to Question Requiring Use of First Law of Thermodynamics

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	**2002** Introductory Physics (Post-test) Interview Sample (*N*=32)	
Correct	**45%**		

Responses to Question Requiring Use of First Law of Thermodynamics

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

Responses to Question Requiring Use of First Law of Thermodynamics

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**	**2002** **Introductory Physics** **(Post-test)** **Interview Sample** **(*N*=32)**	**2004** **Thermal Physics** **(Pretest)** **(*N*=20)**
Correct	**45%**	**34%**	

Responses to Question Requiring Use of First Law of Thermodynamics

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**	**2002** **Introductory Physics** **(Post-test)** **Interview Sample** **(*N*=32)**	**2004** **Thermal Physics** **(Pretest)** **(*N*=20)**
Correct	**45%**	**34%**	**30%**

Responses to Question Requiring Use of First Law of Thermodynamics

	1999-2001 **Introductory Physics** **(Post-test)** **Written Sample** **(*N*=653)**	**2002** **Introductory Physics** **(Post-test)** **Interview Sample** **(*N*=32)**	**2004** **Thermal Physics** **(Pretest)** **(*N*=20)**
Correct	**45%**	**34%**	**30%**
Correct with correct explanation			

Responses to Question Requiring Use of First Law of Thermodynamics

	1999-2001 Introductory Physics (Post-test) Written Sample (*N*=653)	**2002** Introductory Physics (Post-test) Interview Sample (*N*=32)	**2004** Thermal Physics (Pretest) (*N*=20)
Correct	**45%**	**34%**	**30%**
Correct with correct explanation	**11%**	**19%**	**30%**

Responses to Question Requiring Use of First Law of Thermodynamics

	1999-2001 Introductory Physics (Post-test) Written Sample (N=653)	**2002** Introductory Physics (Post-test) Interview Sample (N=32)	**2004** Thermal Physics (Pretest) (N=20)
Correct	**45%**	**34%**	**30%**
Correct with correct explanation	**11%**	**19%**	**30%**

Performance of upper-level students significantly better ($p < 0.01$) than introductory students in *written* sample

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.

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.

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

…

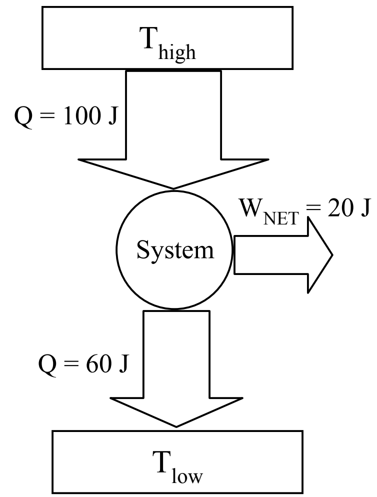
Consider a system composed of a fixed quantity of gas (not necessarily ideal) that undergoes a cyclic process in which the final state is the same as the initial state.

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)

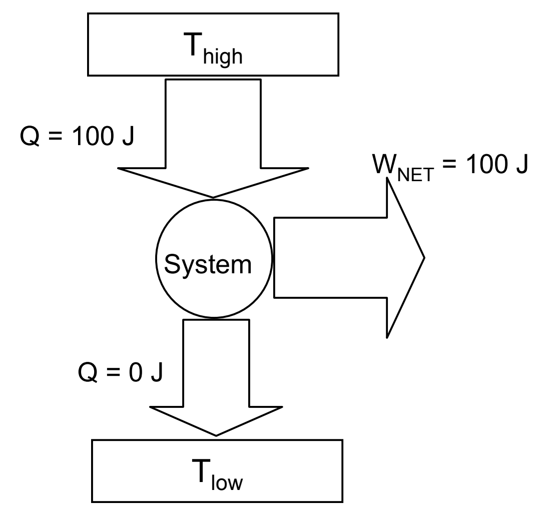
(violation of first law of thermodynamics)

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.

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.

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

Not given

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.

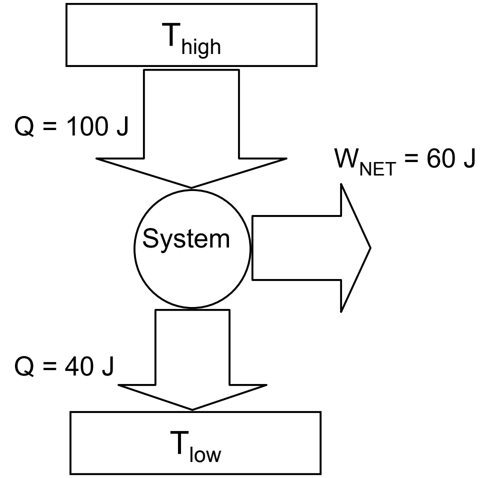
$$\boxed{\Rightarrow \eta_{reversible} = \frac{W}{Q_{in}} = \frac{40}{100} = 0.40 = \eta_{\max}}$$

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.

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.

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.)

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

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?

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 $Q_{\text{reversible}}$ 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 **<u>system</u>** [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 **<u>surroundings</u>** [$S_{surroundings}$] *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%

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.