Overview: Research on Student Learning of Thermal Physics

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References for Research on Learning of Thermal Physics

- Bibliography on Thermodynamics at http://physicseducation.net/current/ [up to 2005]
- Bain, Moon, Mack and Towns, “A review of research on the teaching and learning of thermodynamics at the university level,” Chemistry Education Research and Practice (2014)
- Resource Letter on Teaching Introductory Thermodynamics, under review, by Dreyfus, Geller, Meltzer, and Sawtelle

Guiding Theme

- Many investigations have shown:
  - ➢0-4 weeks of thermal physics in introductory course does not build adequate understanding of fundamental concepts
  - ➢Consequently, initial thinking of upper-level students is tightly coupled to—and largely determined by—ideas developed in the introductory course

Assessment Instruments for Upper-Level Thermal Physics

- There aren’t any
- Even for the introductory course, there are no standard instruments
- However, there are:
  - various instruments for heat and temperature concepts, and heat transfer in engineering contexts
  - a new concept assessment being tested for the introductory course (Chandralekha Singh et al.)
  - many well-tested assessment items for upper-level thermal physics that have not been integrated into a unified instrument

Student Learning of Thermodynamics

Studies of university students have revealed learning difficulties with concepts related to the first and second laws of thermodynamics:

USA
M. E. Loverude, C. H. Kautz, and P. R. L. Heron (2002);
D. E. Meltzer (2004);
M. Cochran and P. R. L. Heron (2006)
Christensen, Meltzer, and Ogilvie (2009)

Finland
Leinonen, Räsänen, Asikainen, and Hirvonen (2009)
Leinonen, Asikainen, and Hirvonen (2013)

Germany
R. Berger and H. Wiesner (1997)
Kautz and Schmitz [engineering context] (2005, 2006, 2007)

France
S. Rozier and L. Viennot (1991)

Turkey
Sözbilir and Bennett [chemistry context] (2007)

UK
J. W. Warren (1972)

General Issues: I

- As in other areas of physics, “everyday language” definitions of certain terms conflict sharply with physics definitions, e.g.:
  - “heat”: common use corresponds more closely to idea of “internal energy”
  - “work”: introductory mechanics context of “force applied to point mass” conflicts with thermodynamics context of boundary deformation
  - “system”: essential yet arbitrary distinction between system and surroundings escapes many students
  - “entropy”: common use as “chaos” or “disorder” is an obstacle to understanding state multiplicities

General Issues: II

- Difficulties with diagrams and symbols causes particular trouble in thermal physics:
  - Confusions between ***quantity*** x and ***change of quantity*** Δx are ubiquitous in thermal physics
  - discomfort with diagrammatic representations is a serious obstacle to effective use of, e.g., pV-diagrams as a tool for understanding and analysis

General Issues III:

- Approximations and idealizations common to thermal physics are intensely confusing for most students, e.g.:
  - “quasistatic” [How slow is that?]
  - “reversible” [Does such a thing really exist?]
  - “reservoir” [Is it *really* at constant temperature? Can there really be “reversible” heat flow?]

In contrast to some other areas of physics, “idealizations” such as these are *fundamental* to understanding of thermal physics

General Issues IV:

- Constraint conditions are ignored and consequently, relationships are overgeneralized:
  - ➢ $\Delta S = \Sigma Q/T$ for ***reversible*** processes
  - ➢ $H = E + PV$; ΔH = heat absorbed in ***constant-pressure*** process
  - ➢ $\Delta G < 0$ for a spontaneous process only holds for ***constant-pressure, constant-temperature*** processes
  - ➢ Etc.

This sort of thing happens *all the time*!
It is a ***highly reliable*** prediction.

Students are Often Confused about "Entry-Level" Ideas

- About 30-50% of introductory students don't realize that objects made of different materials placed in an insulated container will all eventually come to the same temperature (Jasien and Oberem, 2002; Cochran, 2005)
- Many students identity T or ΔT as measures of *heat,* and so constancy (or lack of it) of one is taken to imply the same for the other (e.g., Cochran, 2005)

Students Tend to Adopt Fallacious "Reduction of Variables" Ideas

- Students frequently employ "intuitive" ideas related to oversimplication of multi-variable relationships, e.g.:
  - Assume "higher P → higher T" or "higher T → higher V" [or vice-versa] by ignoring variables in $PV = nRT$ *[Rozier and Viennot, 1991]*
  - Adopt "preferential" dependence of, e.g., entropy on temperature (ignoring volume) or entropy on volume (ignoring temperature) to predict experiment outcomes

1. Initial ideas found among upper-level students, similar or identical to those found among introductory students.

   - Response rates to diagnostic questions on the following items among beginning upper-level students virtually identical to post-instruction responses of students in introductory course

Target Concept, *Work*: System *loses* energy through expansion work, but *gains* energy through compression work.

- Many students believe either that “no work” or *positive* work is done on the system[1,2] during an expansion, rather than negative work.
- Students fail to recognize that system loses energy through work done in an expansion,[2] or that system gains energy through work done in a compression.[1]
- ***Summary:*** Students fail to recognize the energy transfer role of work in thermal context.

[1] Loverude et al., 2002
[2] Meltzer, 2004

Target Concept, *State*: A *state* is characterized by well-defined values for energy and other variables.

- Students seem comfortable with this idea within the context of energy, temperature, and volume, but *not* entropy.[2,3,4]
- Students overgeneralize the state function concept, applying it inappropriately to heat and work.[1,2]
- ***Summary:*** Students are inconsistent in their application of the state-function concept.

[1] Loverude et al., 2002

[2] Meltzer, 2004

[3] Meltzer, 2005 [PER Conf. 2004]

[4] Bucy, et al., 2006 [PER Conf. 2005]

Target Concept, *Isothermal Process*: Isothermal processes involve exchanges of energy with a thermal "reservoir."

- Students do not recognize that energy transfers must occur (through heating) in a quasistatic isothermal expansion.[2,4]
- Students do not recognize that a thermal reservoir does not undergo finite temperature change even when acquiring energy.[2]
- ***Summary:*** Students fail to recognize idealizations involved in definitions of "reservoir" and "isothermal process."

[2] Meltzer, 2004

[4] Leinonen et al., 2009

Target Concept, *Molecular motion:* Temperature is proportional to average kinetic energy of molecules, and inter-molecular collisions can't increase temperature.

- Many students believe that molecular kinetic energy can increase or decrease during an *isothermal* process in which an ideal gas is heated.[2]
- Students believe that intermolecular collisions lead to net increases in kinetic energy and/or temperature.[1,2,3,4]
- ***Summary:*** Students overgeneralize energy *transfer* role of molecular collisions so as to acquire a belief in energy *production* role of such collisions.

[1] Loverude et al., 2002
[2] Meltzer, 2004
[3] Rozier and Viennot, 1991
[4] Leinonen et al., 2009

Target Concept, *Net heat and work*: Both heat transfer and work are process-dependent quantities, whose net values in an arbitrary cyclic process are non-zero.

- Students believe that heat transfers and/or work done in different processes linking common initial and final states must be equal.[1,2]
- Students often believe that that net heat transfer in a cyclic process must be zero since $\Delta T = 0$, and that net work done must be zero since $\Delta V = 0$.[1,2]
- ***Summary:*** Students fail to recognize that neither heat nor work is a state function.

[1] Loverude et al., 2002
[2] Meltzer, 2004

2. Ideas found among upper-level students, different from or not probed in introductory students.

Second Law

- In contrast to introductory students, upper-level students are comfortable with the idea of increasing total entropy. However, they share with them the belief that “system” entropy must increase.
- Most upper-level students are initially able to recognize that “perfect heat engines” (i.e., 100% conversion of heat into work) violate the second law, but…

Second Law

- Most upper-level are initially *unable* to recognize that engines with greater than ideal (“Carnot”) efficiency also violate the second law.
  - Most intermediate students do not recognize connection between constraints on engine efficiencies and entropy change of system and surroundings (Cochran and Heron, 2006)

Issues with Entropy and Equilibrium

- Entropy is sometimes associated with particle collisions (related to "disorder" idea)[1]
- There is a tendency to assume that entropy can't increase in any insulated system [since heating is zero, but forgetting that $\Delta S = \Sigma Q/T$ applies only to reversible processes][1]
- When analyzing changes in available microstates during approach to equilibrium, students tend to ignore the fact that when equilibrium is reached, changes must cease.

[1] Sozbilir and Bennett, 2007

Entropy in Cyclic Processes

- After (special) instruction, most upper-level students recognize impossibility of super-efficient engines, but still have difficulties understanding cyclic-process requirement of $\Delta S = 0$; many also still confused about $\Delta U = 0$.

- On cyclic process questions involving heat engines, most (60%) upper-level students claim that net change in entropy is *not* zero, because they apply $\Delta S = \Sigma Q/T$ even when the process is not reversible; also, they ignore the state-function property of entropy which says $\Delta S = 0$ since initial and final states are identical.

Free Expansion and Equilibrium

- Even after extensive work on free-expansion processes, upper-level students show poor performance (< 50% correct)
  - frequent errors: belief that temperature or internal energy must change, work is done, etc.
  - difficulties with first-law concepts prevented students from realizing that T does not change

Maxwell Relations and Boltzmann Factor

- Few students recognize when a physical situation calls for the use of a Maxwell relation, and even fewer are able to select the appropriate Maxwell relation.[1]
- Students often do not recognize situations in which the Boltzmann factor is appropriate, nor do they understand where the mathematical expression comes from.[2]

[1] Thompson, Bucy, and Mountcastle, 2006 [PER Conf. 2005]

[2] Smith, Thompson, and Mountcastle, 2010 [PER Conf. 2010]

Statistical Concept Challenges

- Concepts in statistics can be challenging and unfamiliar to many students.
  - Understanding of multiplicities, distinguishing between microstates and macrostates
  - Recognizing the narrowing of a distribution as N increases

Thermal Physics Project

(Christensen, Loverude, Meltzer, and Thompson; originally with T. Greenbowe)

A 15-year project to study student learning of topics in thermal physics and develop instructional materials based on the research.

- Investigate student understanding of key topics in thermal physics
- Develop tutorials and supporting materials on target topics
- Assess and document effectiveness of curriculum and revise as needed

Primary Goals:

- Develop and validate assessment questions to probe student understanding
- Document student understanding before and after standard instruction
- Identify key learning difficulties and instructional interventions

Primary research methods:

- Written and online assessment questions
- Semi-structured student interviews

Instructional/Curricular Materials

- *Tutorials* ("University of Washington-style") make use of small group guided-inquiry activities
- Students work in groups (2-4) on structured worksheets, while instructor interacts with groups to respond to questions, clarify issues, and check reasoning.
- Curricular emphases:
  - addressing student difficulties, constructing concepts
  - developing reasoning ability (qualitative and quantitative)
  - making connections between theory and phenomena, NOT solving standard quantitative exercises

Available Tutorials (all “UW-style”)

UW

Ideal Gas Law
First Law of Thermodynamics

CSUF

Microscopic Model for an Ideal Gas
Enthalpy [also available as HW-only worksheet]
Counting States (binomial)
States in the Einstein Solid
Energy, Entropy, and Temperature
Entropy
Engines and Refrigerators
Maxwell Relations and Thermodynamic Potentials
Phase Diagram of a Pure Substance
Boltzmann Factor [targeted to Schroeder approach]

Maine/ISU/ASU/NDSU

Partial Derivatives and Material Properties
Multiplicities and Probabilities for Outcomes of Binary Events
Introduction to Entropy [intro and upper-division versions]
State Function Property of Entropy [intro and upper-division versions]
Heat Engines
Boltzmann Factor

Some Sample Data…

Findings from Entropy Questions

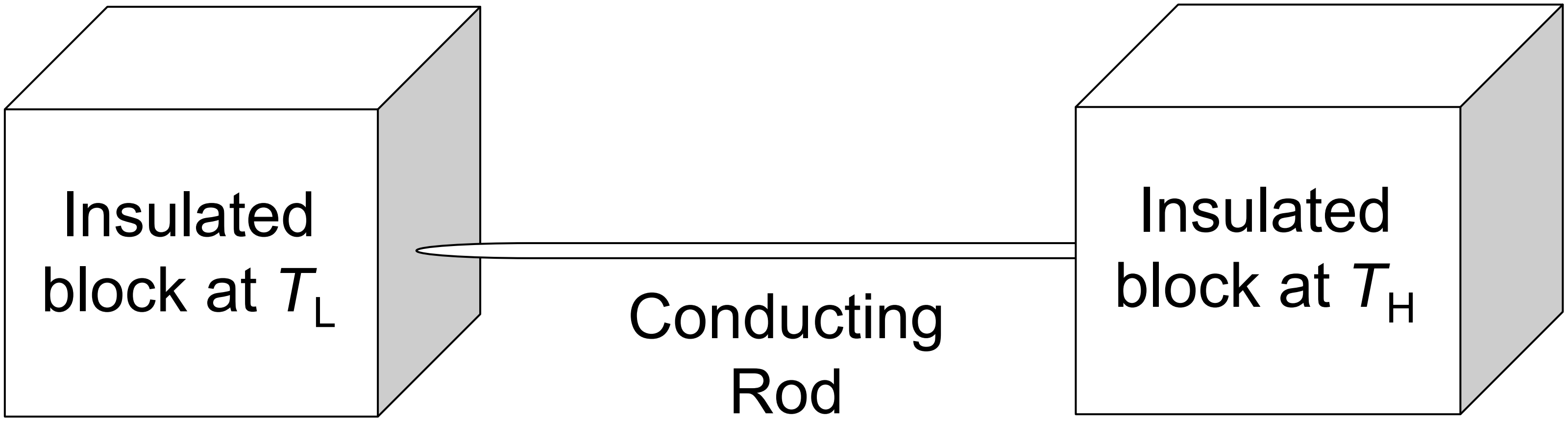
Both before and after instruction…

In both a general and a concrete context:

- Introductory students have significant difficulty applying fundamental concepts of entropy
- More than half of all students utilized inappropriate conservation arguments in the context of entropy

“Two-Blocks” Entropy Tutorial

(draft by W. Christensen and DEM, undergoing class testing)



Insulated block at T_L

Conducting Rod

Insulated block at T_H

- Consider slow heat transfer process between two thermal reservoirs (insulated metal block connected by thin metal pipe)
    - ➢Does total energy change during process? *[No]*
    - ➢Does total entropy change during process? *[Yes]*

Entropy Tutorial

(draft by W. Christensen and DEM, undergoing class testing)

- Guide students to find that:

$$\Delta S_{total} = \frac{Q}{T_{cold\ reservoir}} - \frac{Q}{T_{hot\ reservoir}} > 0$$

and that definitions of "system" and "surroundings" are arbitrary

Preliminary results are promising…

Entropy Tutorial

(draft by W. Christensen and DEM, undergoing class testing)

- Guide students to find that:

  Entropy gain of low-temperature block is *larger* than entropy loss of high-temperature block, so *total entropy increases*

  and that definitions of "system" and "surroundings" are arbitrary

Preliminary results are promising…

General-Context Question

[Introductory-Course Version]

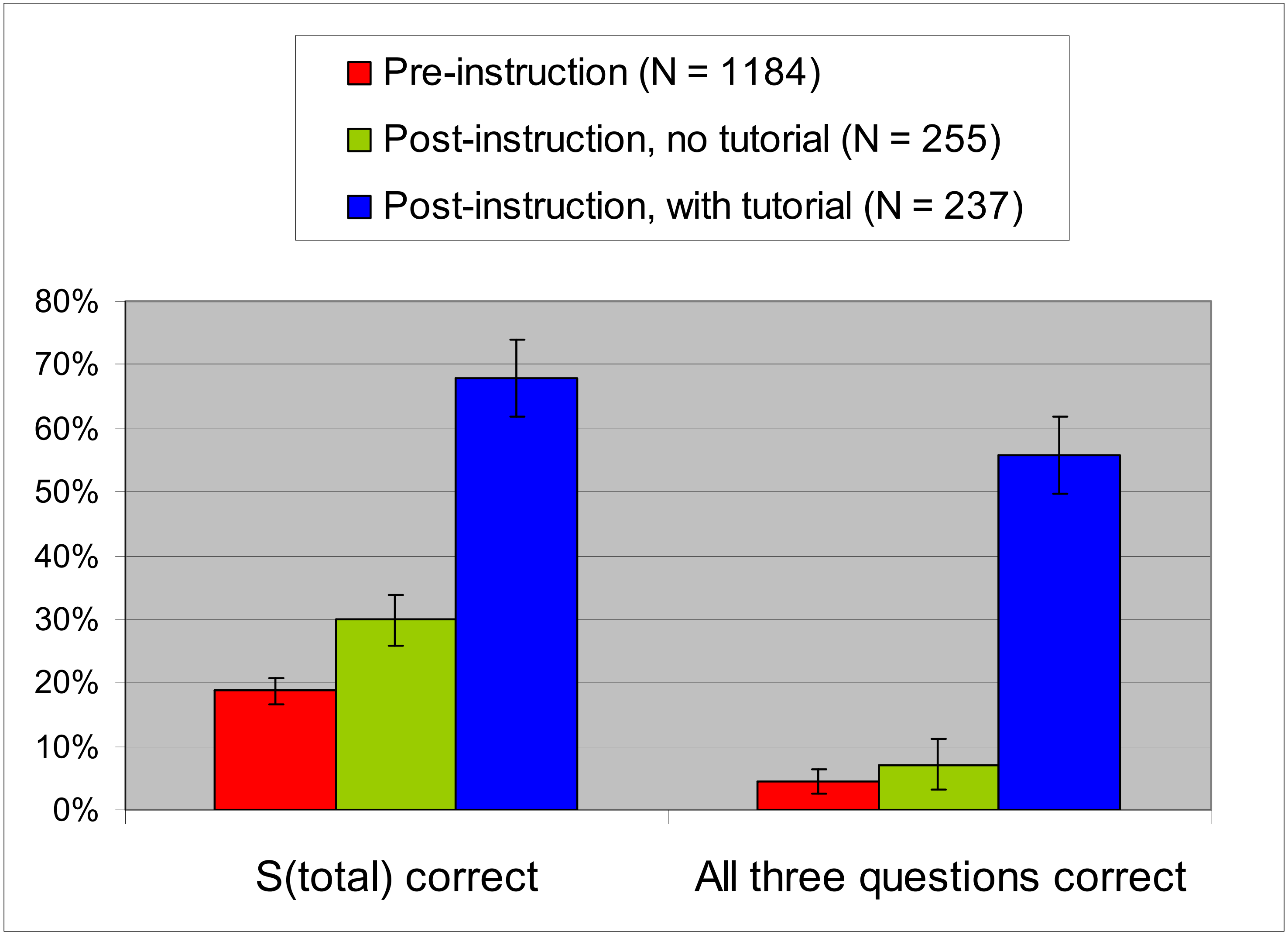
For each of the following questions consider a system undergoing a naturally occurring (“spontaneous”) process. The system can exchange energy with its surroundings.

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.***

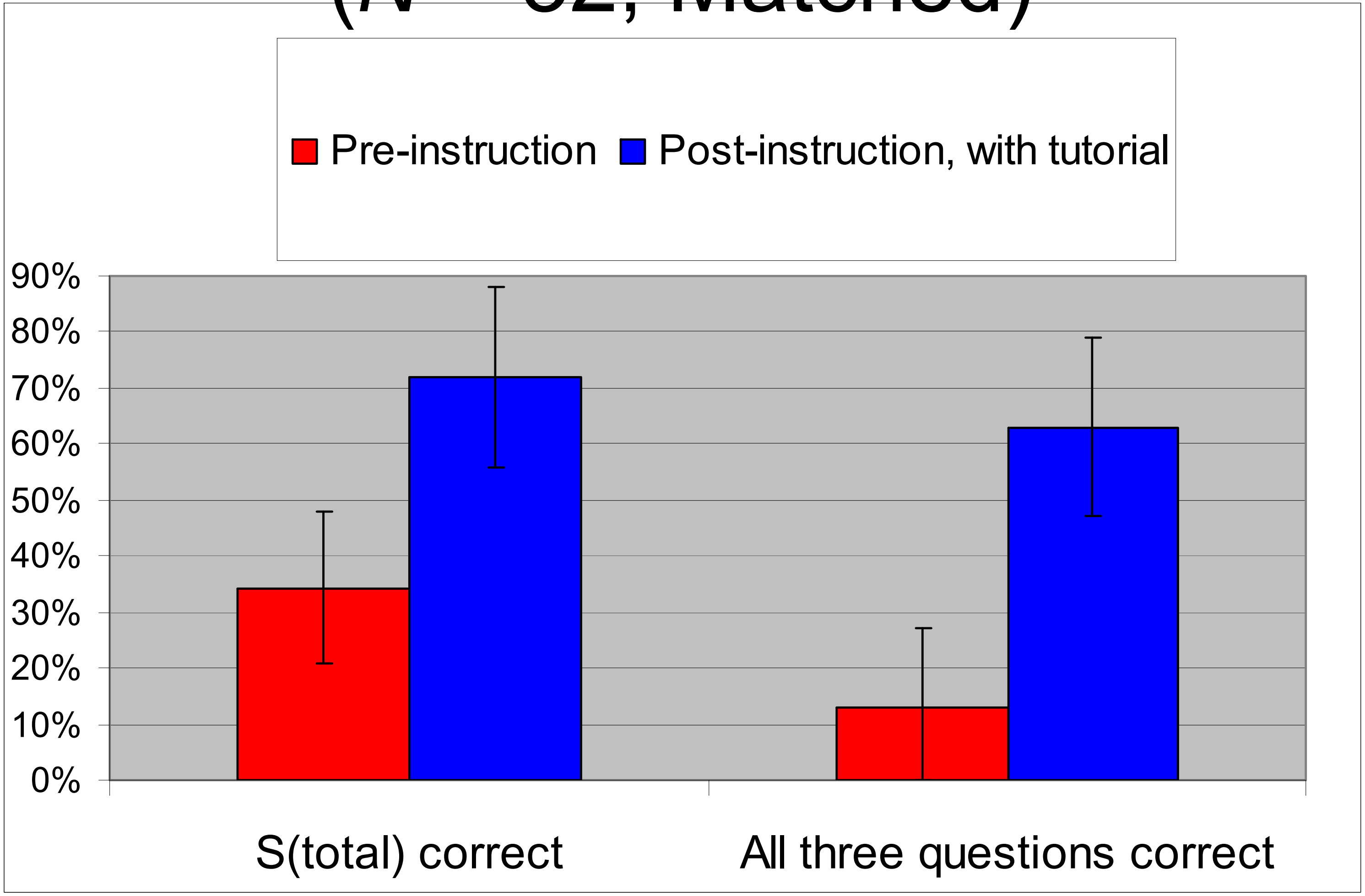
C. During this process, does the entropy of the system *plus* the entropy of the surroundings [$S_{system} + S_{surroundings}$] [✓ *increase*,] *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

Responses to General-Context Question **Introductory** Students



Responses to General-Context Question **Intermediate** Students

(*N* = 32, Matched)



Summary

- Many upper-level students initially share key conceptual difficulties manifested by introductory students
- Certain difficulties persist even after extensive instruction in upper-level courses.
- For more information, see: http://thermoper.wikispaces.com/