Investigations into Student Learning of Thermodynamics

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Collaborators

– Tom Greenbowe (Iowa State University, Chemistry)
– John Thompson (U. Maine Physics)

Students

– Ngoc-Loan Nguyen (ISU, M.S. 2003)
– Warren Christensen (ISU Ph.D. student)

Funding

– NSF Division of Undergraduate Education
– NSF Division of Physics

Physics Education As a Research Problem

Within the past 25 years, physicists have begun to treat the teaching and learning of physics as a research problem

- Systematic observation and data collection; reproducible experiments
- Identification and control of variables
- In-depth probing and analysis of students' thinking

Physics Education Research ("PER")

Physics Education Research and Chemical Education Research: Common Themes

- **Physics Education Research:** Approximately 80 physics departments in the U.S. carry out work in PER; 12-15 award Ph.D. degrees
- **Chemical Education Research:** About two dozen M.A. and Ph.D. programs in CER in the U.S.
- Analogous goals, similar research methods
- Great potential for collaborative work

See: P. Heron and D. Meltzer, *CHED Newsletter*, Fall 2005, 35-37

Some Specific Issues

Many (if not most) students:

- develop weak ***qualitative*** understanding of concepts
  - don't use qualitative analysis in problem solving
  - lacking quantitative problem solution, can't reason "physically"

- often encounter specific learning difficulties—"alternative conceptions"—that hinder their understanding of targeted concepts

Example:
Student Learning of Thermodynamics in Physics

Recent studies of university students in general physics courses showed substantial learning difficulties with fundamental concepts, including heat, work, cyclic processes, and the first and second laws of thermodynamics.*

M. E. Loverude, C. H. Kautz, and P. R. L. Heron, Am. J. Phys. ***70**, 137 (2002);*

D. E. Meltzer, Am. J. Phys. ***72**, 1432 (2004);*

M. J. Cochran and P. R. L. Heron, Am. J. Phys. ***74**, 734 (2006).*

Performance Comparison: Introductory Students vs. Advanced Students

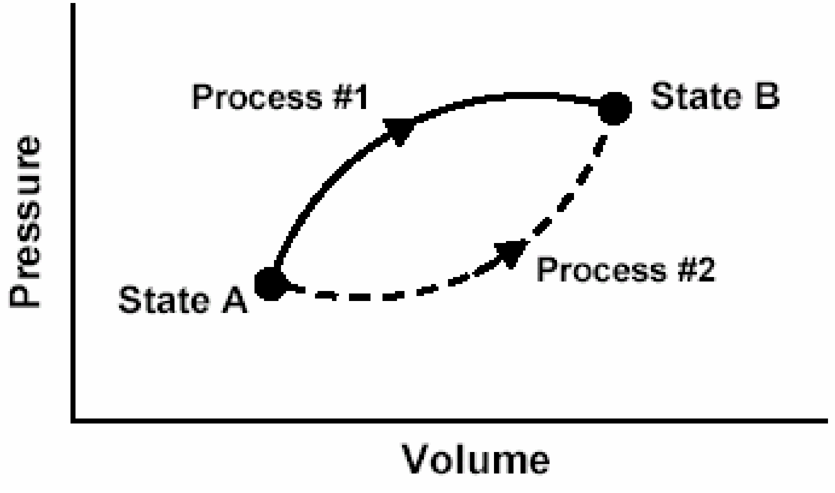
- **Introductory course:** second-semester general physics course with calculus at Iowa State, primarily engineering majors

- **Advanced course:** junior/senior-level Thermal Physics course at Iowa State, almost all physics majors or physics/engineering double majors

Performance Comparison: Introductory Students vs. Advanced 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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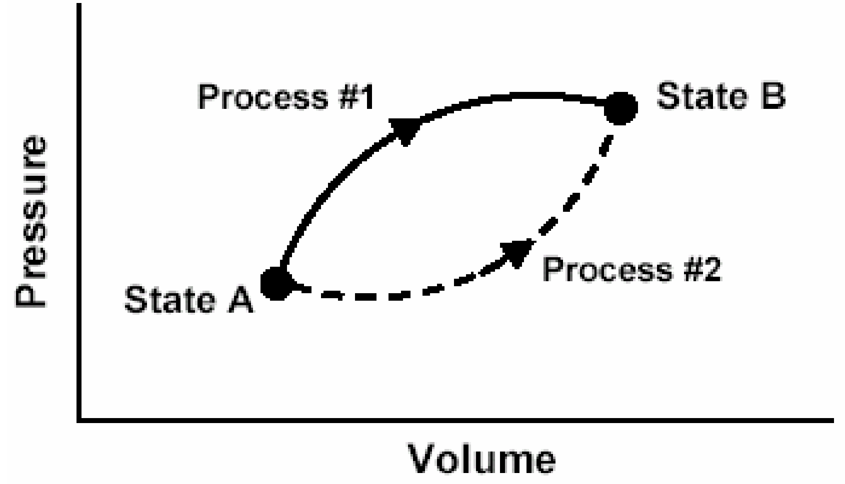

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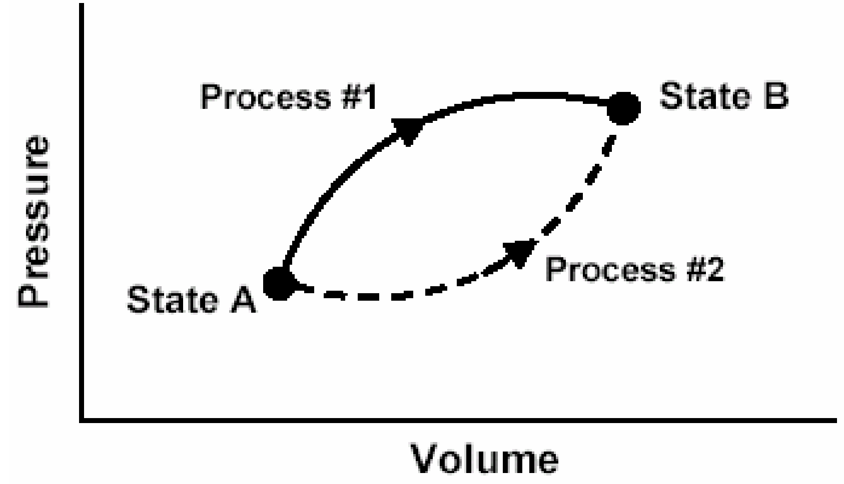

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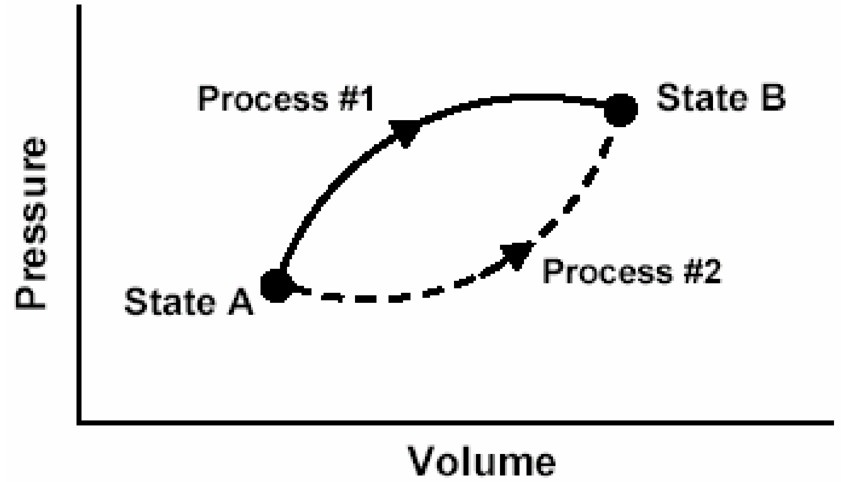

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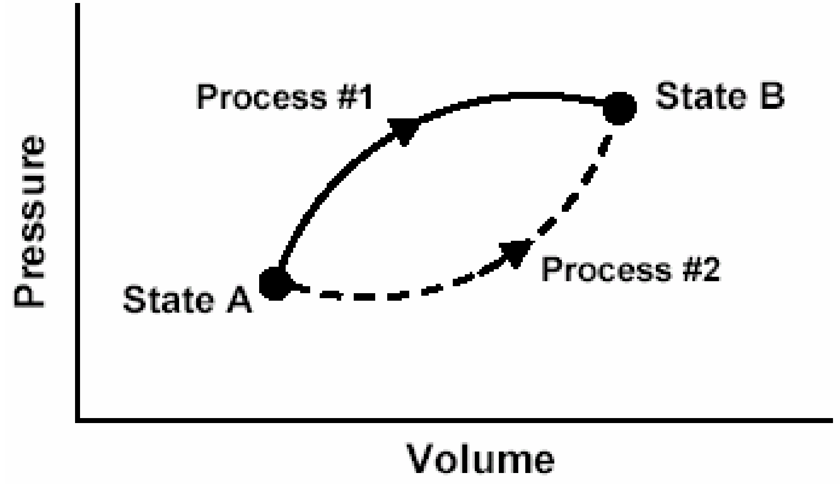

$$W_1 > W_2$$

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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)	**2003-4** Thermal Physics (Pretest) (*N*=33)
$W_1 = W_2$	**30%**	**22%**	**21%**

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

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)	2005 Physical Chemistry (Post-test) (*N*=8)
$W_1 = W_2$	30%	22%	75%

Physical Chemistry course (University of Maine): consistent with Towns and Grant (1997)

Explanations Given by Thermal Physics Students to Justify $W_1 = W_2$

- "*Equal, path independent*."
- "*Equal, the work is the same regardless of path taken*."

Some students come to associate work with phrases only used in connection with state functions.

Explanations similar to those offered by introductory students

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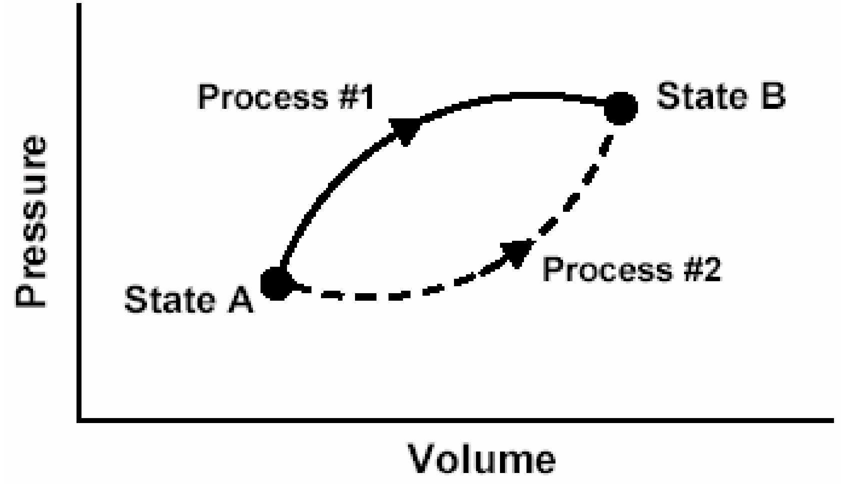

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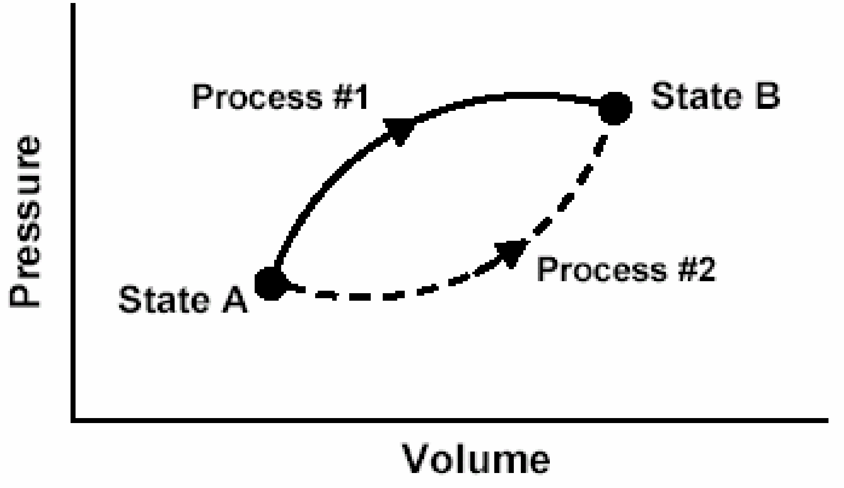
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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



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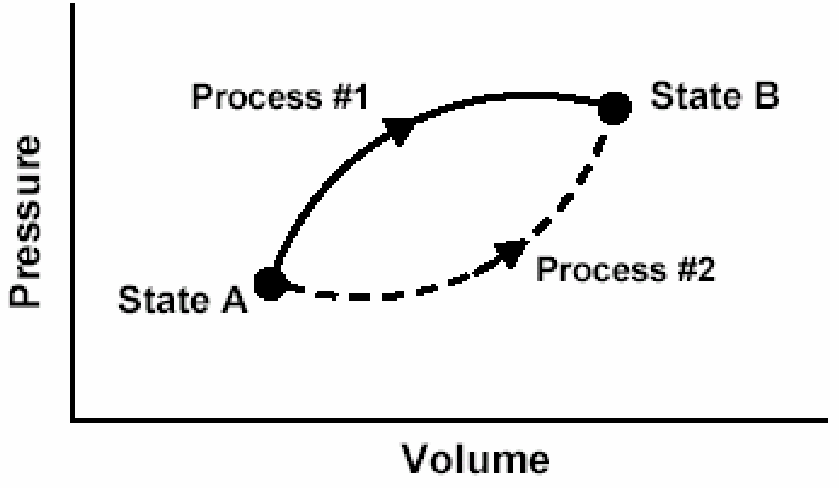
This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes two ***different*** processes in going from state A to state B:

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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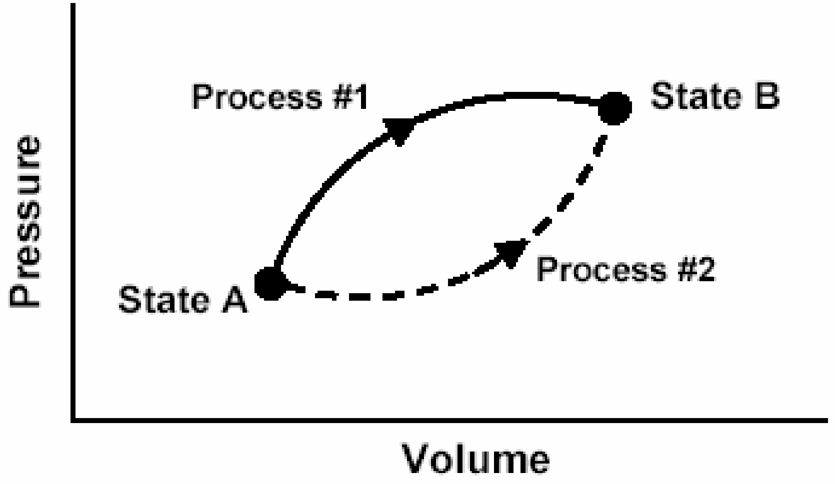
Algebraic Method:

$$\Delta E_1 = \Delta E_2$$

$$Q_1 - W_1 = Q_2 - W_2$$

$$W_1 - W_2 = Q_1 - Q_2$$

$$W_1 > W_2 \Rightarrow Q_1 > Q_2$$



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Responses to Diagnostic Question #2

(Heat question)

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$Q_1 > Q_2$	45%	34%	33%

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)**	**2003-4** **Thermal Physics** **(Pretest)** **(*N*=33)**
$Q_1 > Q_2$	**45%**	**34%**	**33%**
Correct or partially correct explanation	**11%**	**19%**	**30%**

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Performance of upper-level students better than that of most introductory students, but still weak

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Most popular incorrect answer is that heat is *independent* of process so that $Q_1 = Q_2$

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Post-test performance of Physical Chemistry students at University of Maine comparable to introductory course

Primary Findings, Introductory Physics Course

*Even **after** instruction, many students (40-80%):*

- believe that heat and/or work are state functions independent of process
- are unable to apply the First Law of Thermodynamics in problem solving

Example: Student Learning of Thermodynamics in Chemistry and Physics

[with T. J. Greenbowe]

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Previous Investigations of Learning in Chemical Thermodynamics
(upper-level courses)

- A. C. Banerjee, “Teaching chemical equilibrium and thermodynamics in undergraduate general chemistry classes,” J. Chem. Ed. **72**, 879-881 (1995).

- M. F. Granville, “Student misconceptions in thermodynamics,” J. Chem. Ed. **62**, 847-848 (1985).

- P. L. Thomas, and R. W. Schwenz, “College physical chemistry students’ conceptions of equilibrium and fundamental thermodynamics,” J. Res. Sci. Teach. **35,** 1151-1160 (1998).

Example: Student Learning of Thermodynamics in **Chemistry** and Physics

[with T. J. Greenbowe]

1. Learning of thermochemical concepts in the context of calorimetry
2. Conceptual confusion regarding free energies

Example: Student Learning of Thermodynamics in **Chemistry** and Physics [with T. J. Greenbowe]

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Learning of Thermochemical Concepts in Context of Calorimetry

T. J. Greenbowe and D. E. Meltzer, Int. J. Sci. Educ. *25, 779 (2003)*

- Investigated students' misunderstanding of role of bond breaking and forming in determining heats of reaction
  - *belief that heat flows <u>from</u> one reactant <u>to</u> the other*
- Uncovered students' misinterpretation of role of mass in relationship $Q = mc\Delta T$
  - *tendency to associate* "m" *with reactants only, instead of with total mass undergoing temperature change*

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Student learning of thermochemical concepts in the context of solution calorimetry

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Student understanding of heat and thermal phenomena has been the subject of considerable investigation in the science education literature. Published studies have reported student conceptions on a variety of advanced topics, but calorimetry – one of the more elementary applications of thermochemical concepts – has apparently received little attention from science education researchers. Here we report a detailed analysis of student performance on solution calorimetry problems in an introductory university chemistry class. We include data both from written classroom exams for 207 students, and from an extensive longitudinal interview series with a single subject who was herself part of that larger class. Our findings reveal a number of learning difficulties, most of which appear to originate from failure to understand that net increases and decreases in bond energies during aqueous chemical reactions result in energy transfers out of and into, respectively, the total mass of the resultant solution.

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Calorimetry Problem on Final Exam

The following reaction takes place at constant pressure in an insulated calorimeter: 1.00 L of 2.00 M $Ba(NO_3)_2$ solution at 25.0°C was mixed with 1.00 L of 2.00 M Na_2SO_4 solution at 25.0°C. The final temperature of the solution after mixing was 31.2°C. Assume that all solutions had a density of 1.00 g/mL and a specific heat of 4.18 J/g-°C.

Calculate the heat of reaction (in kJ).

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Very similar question included on second hour exam

Solution to Final Exam Question

$$m = \rho V = (1.00\,\text{g/ mL})\left(2\times10^{3}\,\text{mL}\right) = 2\times10^{3}\,\text{g}$$

$$\begin{aligned} q_{soln} &= mc\Delta T \\ &= \left(2\times10^{3}\,\text{g}\right)\left(4.18\,\text{J/ g–}^{\circ}\text{C}\right)\left(+6.2^{\circ}\text{C}\right) \\ &= +52\,\text{kJ} \end{aligned}$$

$$q_{rxn} = -q_{soln} = -52\,\text{kJ}$$

Responses on Heat of Reaction Questions

	Second Hour Exam	Final Exam
	n = 185	n = 207
Correct or nearly correct magnitude of q_{rxn}	50%	40%
Errors using formula		
Set $q = \Delta T$ (or $q = T$)	8%	5%
Did not use $q = mc\Delta T$ or $q = \Delta T$	11%	9%
Errors in value for mass		
Used mass of the reactants only	15%	21%
Used mass of one solution only	8%	5%
Other Responses	7%	15%
No answer	2%	6%

Difficulties with Calorimetry Problems

- Most students did not provide correct sign (negative) for heat of reaction in this exothermic process.
- About 15-20% of students did not realize the need to use $q = mc\Delta T$.
- About 25% of all students did not realize that mass *m* refers to total mass of solution in container.

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Examples from Interviews

Q: *What are you measuring with the thermometer?*

Sophia: The heat is rising in the solution because something is letting off heat but it is going into solution. There is a transfer of heat. It is going from one object to another.

Q: *And what is that object to the other?*

Sophia*:* It is from one chemical to the other but I am not sure which is giving it off and which is absorbing it.

Examples from Interviews

Sophia: …say we had the magnesium and we pour HCl(aq) on it. I would then know where one thing is going to the other.

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Sophia: …say we had the magnesium and we pour HCl(aq) on it. I would then know where one thing is going to the other. Because if the solution gains heat when you put Mg in the hydrochloric acid, then we know that the liquid solution is absorbing the heat, from the solid to the aqueous solution. But, when we have two aqueous solutions, then I don't know which is giving the heat and which one is absorbing the heat.

Examples from Interviews

Q: *What is this* q*?* [heat of reaction produced during reaction of magnesium metal and hydrochloric acid]

Sophia: *"q"* is heat. Heat of the reaction.

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Examples from Interviews

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Sophia: *"q"* is heat. Heat of the reaction. So this heat is what is given off by the magnesium and transferred to the hydrochloric acid solution. The magnesium gives or transfers heat to the 6 M HCl solution and that is why the solution gets warm. And you can see it happening because the magnesium reacts with the HCl and gives bubbles. The magnesium is where the reaction is taking place because you can see it happening!

Other Reports of Student Difficulties Regarding Bond Breaking and Forming

- Martins and Cachapuz (1993): high-school and college chemistry students in Portugal
- Boo (1998) and Boo and Watson (2001): Grade 12 students in UK
- Barker and Millar (2000): high-school graduates in the UK
- Ebenezer and Fraser (2001): university engineering students in South Africa

Some Specific Issues

Many (if not most) students:

- develop weak ***qualitative*** understanding of concepts
  - don't use qualitative analysis in problem solving
  - lacking quantitative problem solution, can't reason "physically"

- often encounter specific learning difficulties—"alternative conceptions"—that hinder their understanding of targeted concepts

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But … *some* students learn efficiently . . .

- Highly successful physics and chemistry students are ***"active learners."***
  - they continuously probe their own understanding

    [*pose their own questions; scrutinize implicit assumptions; examine varied contexts; etc.]*

  - they are sensitive to areas of confusion, and have the confidence to confront them directly

- Majority of introductory students are unable to do efficient active learning on their own: they don't know "which questions they need to ask"
  - they require considerable assistance from instructors, aided by appropriate curricular materials

Research in physics and chemistry education suggests that:

- “Teaching by telling” has only limited effectiveness
  - *listening and note-taking have relatively little impact*

- Problem-solving activities with rapid feedback yield improved learning gains

- Eliciting and addressing common conceptual difficulties improves learning and retention

Active-Learning Pedagogy

(“*Interactive Engagement*”)

- problem-solving activities during class time
  - student group work
  - frequent question-and-answer exchanges with instructor
- “*guided-inquiry*” methodology: guide students through structured series of problems and exercises, offering aid through “Socratic” questioning

Goal: Guide students to “figure things out for themselves” as much as possible

Key Themes of Research-Based Instruction

- Emphasize qualitative, non-numerical questions to reduce unthoughtful “plug and chug.”
- Make extensive use of multiple representations to deepen understanding.

  (Graphs, diagrams, words, simulations, animations, etc.)

- Require students to *explain their reasoning* (verbally or in writing) to more clearly expose their thought processes.

Implementation of Instructional Model

"Elicit, Confront, Resolve" (U. Washington)

- Pose questions to students in which they tend to encounter common conceptual difficulties
- Allow students to commit themselves to a response that reflects conceptual difficulty
- Guide students along reasoning track that bears on same concept
- Direct students to compare responses and resolve any discrepancies

Implementation of Instructional Model

"Elicit, Confront, Resolve" (U. Washington)

→ *One of the central tasks in curriculum reform is development of "Guided Inquiry" worksheets*

- Worksheets consist of sequences of closely linked problems and questions
  - *focus on conceptual difficulties identified through research*
  - *emphasis on qualitative reasoning*
- Worksheets designed for use by students working together in small groups (3-4 students each)
- Instructors provide guidance through "Socratic" questioning

Thermochemistry Instructional Strategy

“Elicit, Confront, Resolve”

- Elicit students’ explanations for source of heats of reaction.

- Allow students to grapple with common misconception that heat of reaction arises through heat flow ***from*** one reactant ***to*** another.

- Guide students to resolve discrepancies by using concept of bond forming and breaking.

Thermochemistry Tutorial

The textbook (p. 161) describes an experiment in which Silver Nitrate ($AgNO_3$) solution is mixed with hydrochloric acid (HCl) solution in a constant-pressure calorimeter. (We assume that the calorimeter loses only a negligible quantity of heat.) The temperature of the resulting solution is observed to increase, due to the following reaction:

$$AgNO_3(aq) + HCl(aq) \rightarrow AgCl(s) + HNO_3(aq)$$

2. Three students are discussing this experiment. Here is part of their discussion:

Mary: The silver nitrate was originally a solid. When it's put into solution along with the HCl, I think that heat flows out from the $AgNO_3$ and into the HCl solution, and that's why the temperature increases.

Bob: Well, the hydrochloric acid is the more powerful reactant; it's a strong acid, so it must be the one that reacts most strongly. I think that the heat must come out of the HCl.

Lisa: I don't really think that the heat flows into either of those two. I think heat flows out of both the silver nitrate *and* the hydrochloric acid solution, and that's why the temperature rises.

Mary: But how could heat flow out of *both* of the reactants? Where is it coming from then? Doesn't that violate conservation of energy?

Comment on the students' statements. Do you agree with one of them more than the others? If so, explain why. If you don't think that any of them are completely correct, give your own opinion.

Excerpt from Worksheet

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During this reaction, does energy flow *into* the resulting solution (if so, where did the energy come from?), *out of* the solution (if so, where did it go?), or is there *no net flow of energy* into or out of the solution (if so, how do you know?).

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Lisa: I don't really think that the heat flows into either of those two. I think heat flows out of both the silver nitrate *and* the hydrochloric acid solution, and that's why the temperature rises.

Mary: But how could heat flow out of *both* of the reactants? Where is it coming from then? Doesn't that violate conservation of energy?

Comment on the students' statements. Do you agree with one of them more than the others? If so, explain why. If you don't think that any of them are completely correct, give your own opinion.

Example: Student Learning of Thermodynamics in **Chemistry** and Physics
[with T. J. Greenbowe]

1. Learning of thermochemical concepts in the context of calorimetry

2. Conceptual confusion regarding free energies

Example: Student Learning of Thermodynamics in **Chemistry** and Physics

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Student Understanding of Entropy and the Second Law of Thermodynamics in the Context of Chemistry

- Second-semester course at Iowa State University; covered standard topics in chemical thermodynamics:
  - Entropy and disorder
  - Second Law of Thermodynamics:

    $$\Delta S_{universe} \; [= \Delta S_{system} + \Delta S_{surroundings}] \geq 0$$
  - Gibbs free energy: $G = H - TS$
  - Spontaneous processes: $\Delta G_{T,P} < 0$
- Written diagnostic administered to 47 students (11% of class) last day of class.
- In-depth interviews with eight student volunteers

Students' confusion:
apparently conflicting criteria for spontaneity

- $\Delta G_{T,P} < 0$ criterion, and equation $\Delta G = \Delta H - T\Delta S$, refer only to properties of the ***system;***

- $\Delta S_{universe} > 0$ refers to properties ***outside*** the system;

  → *Consequently, students are continually confused as to what is the "system" and what is the "universe," and* ***which one*** *determines the criteria for spontaneity.*

Overall Conceptual Gaps

- There is uncertainty as to whether a spontaneous process requires entropy of the ***system*** or entropy of the ***universe*** to increase.

- There is uncertainty as to whether $\Delta G < 0$ implies that entropy of the ***system*** or entropy of the ***universe*** will increase.

Example: Student Learning of Thermodynamics in Chemistry and Physics

Example: Student Learning of Thermodynamics in Chemistry and **Physics**

Example: Student Learning of Thermodynamics in Chemistry and **Physics**

[with John Thompson and Warren Christensen]

- Introductory Course

  (general physics for engineers)

- Intermediate Course

  (sophomore-level thermal physics, mostly physics majors)

- Advanced Course

  (junior/senior-level thermal physics course for physics majors)

Spontaneous Process Question

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

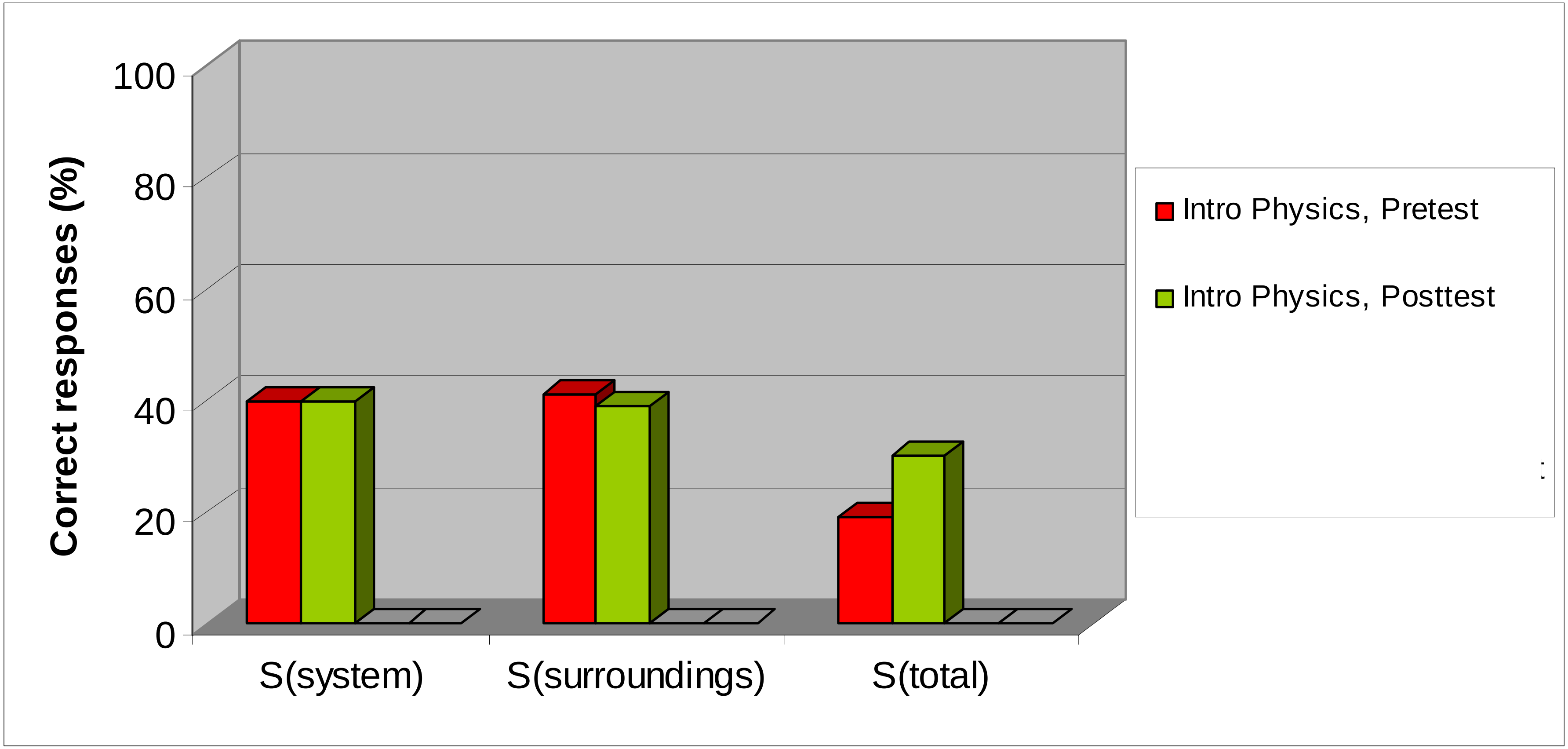
A. During this process, does the entropy of the **system** [S_{system}] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

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 Questions

Introductory Students



Less than 40% correct on each question

Introductory Physics Students' Thinking on Spontaneous Processes

- Tendency to assume that "system entropy" must *always* increase

- Slow to accept the idea that entropy of system plus surroundings ***increases***

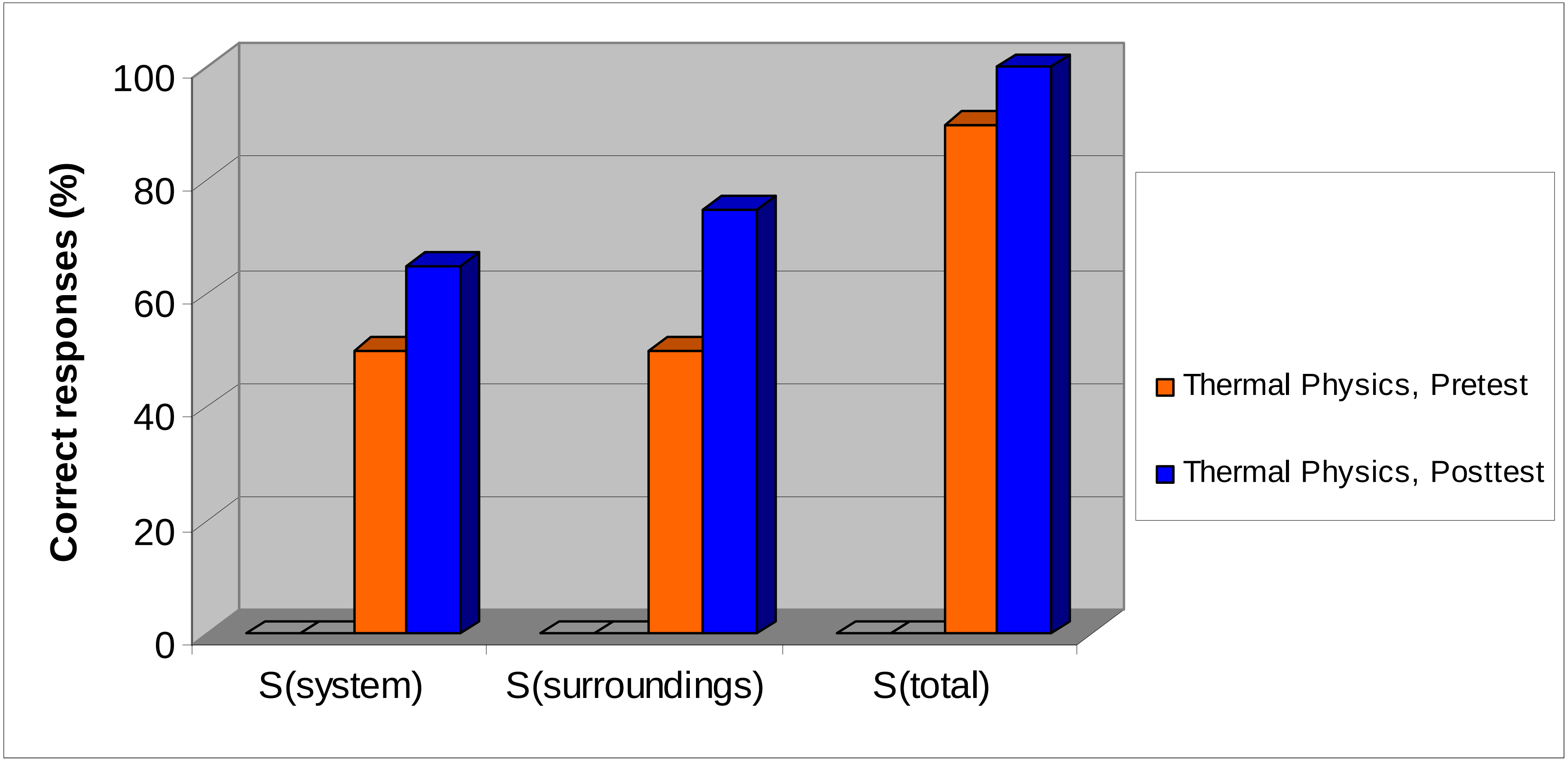
  - *Most students give incorrect answers to all three questions*

Introductory Physics Students' Thinking on Spontaneous Processes

- Tendency to assume that "system entropy" must *always* increase
- Slow to accept the idea that entropy of system plus surroundings ***increases***
  - *Consistent with findings of Thomas and Schwenz (1998) in physical chemistry course*

Responses to Spontaneous-Process Questions

Advanced Students



Thermal Physics Posttest: Interactive Engagement, no focused tutorial

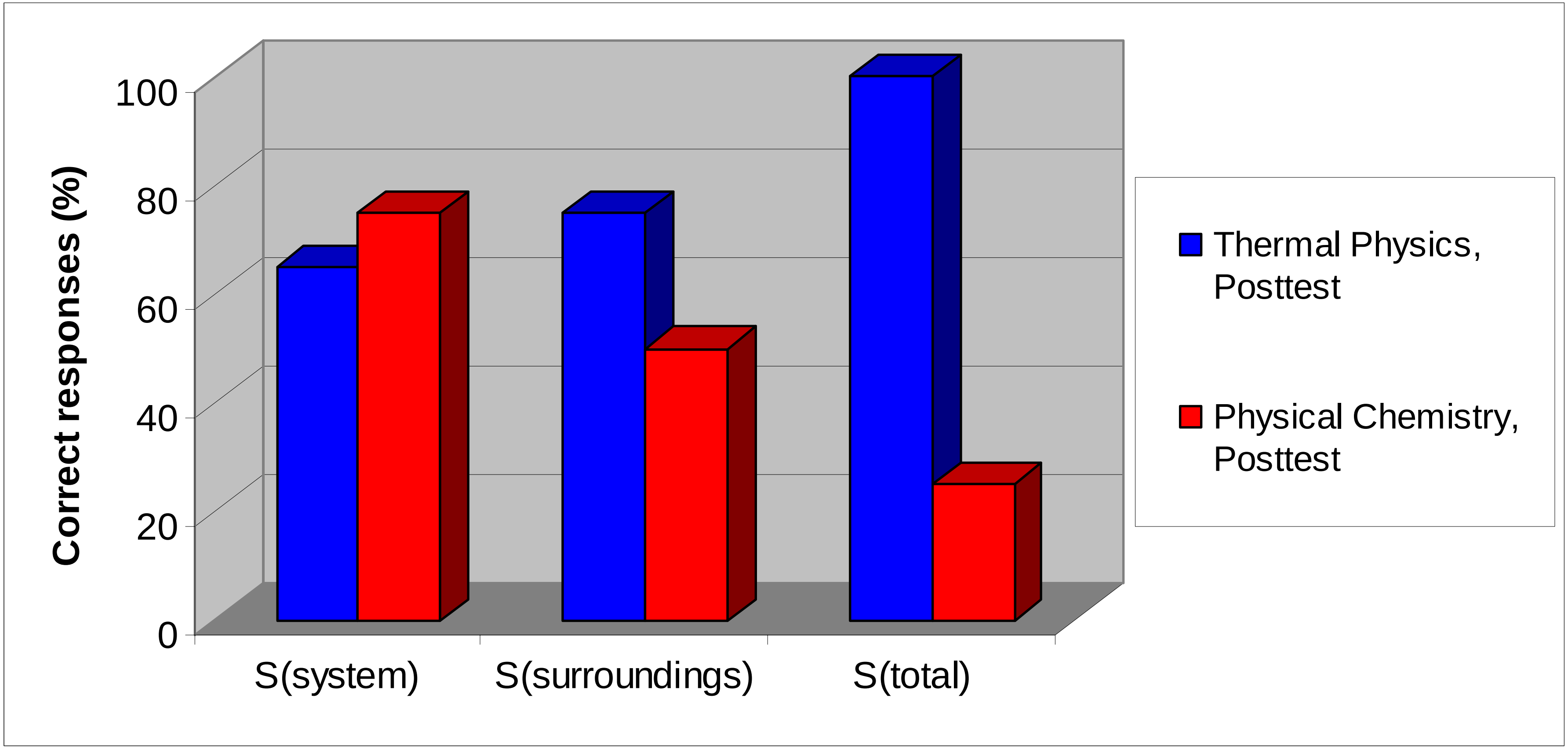
Thermal Physics Students' Thinking on Spontaneous Processes

- Readily accept that "entropy of system ***plus*** surroundings increases"
  - in contrast to introductory students

- Tendency to assume that "system entropy" must *always* increase
  - similar to thinking of introductory students

Responses to Spontaneous-Process Questions

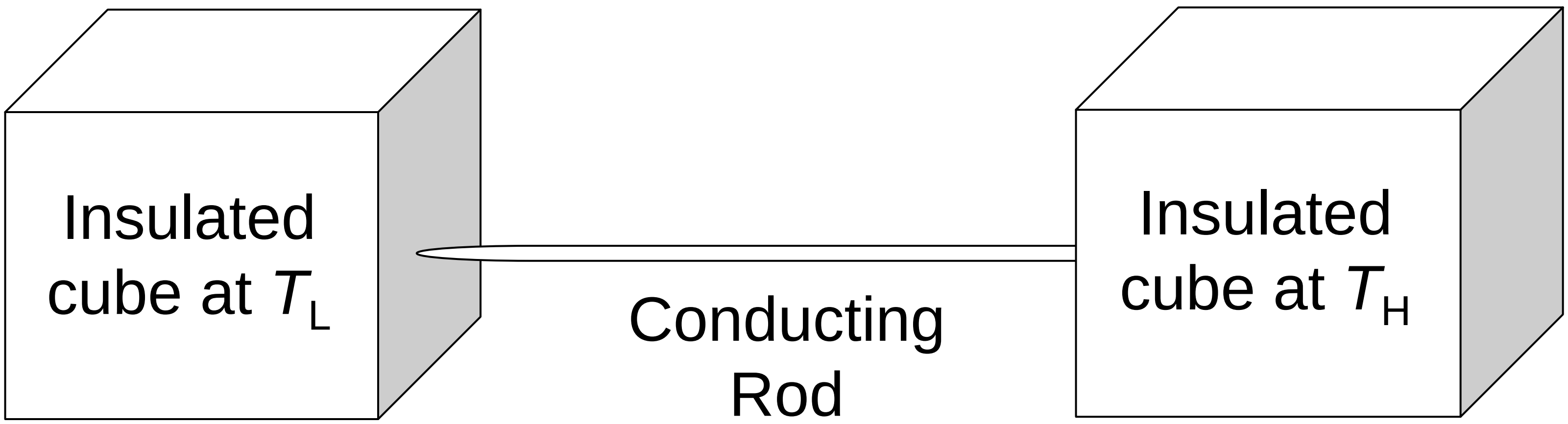
Thermal Physics Students vs. Physical Chemistry Students: Posttest



[Physical Chemistry, U. Maine, 2005; consistent with Thomas and Schwenz (1998)]

Entropy Tutorial

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



- Consider slow heat transfer process between two thermal reservoirs (insulated metal cubes connected by thin metal pipe)
    - ➢Does total energy change during process?
    - ➢Does total entropy change during process?

Entropy Tutorial

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

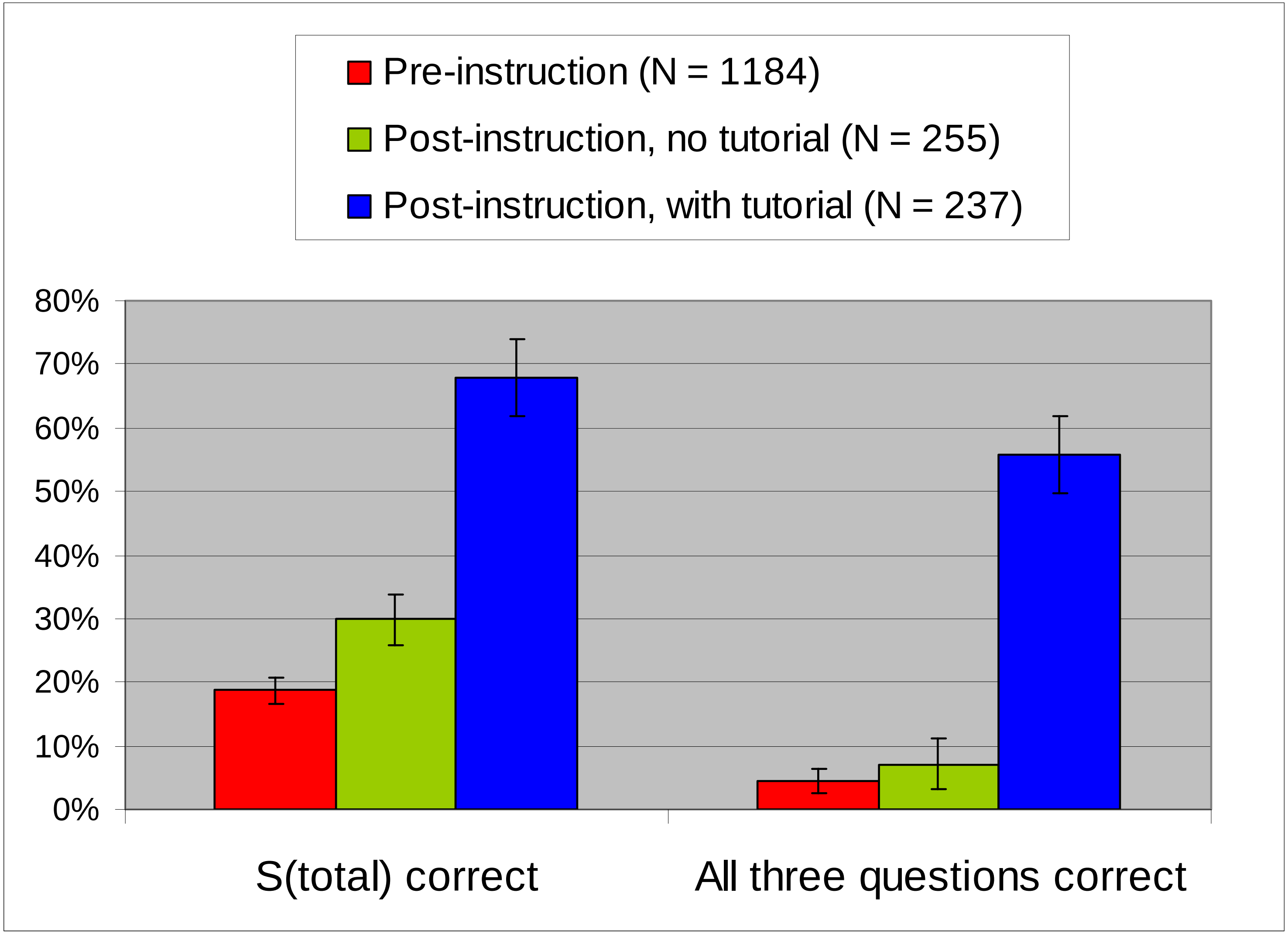
- Guide students to find that:

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

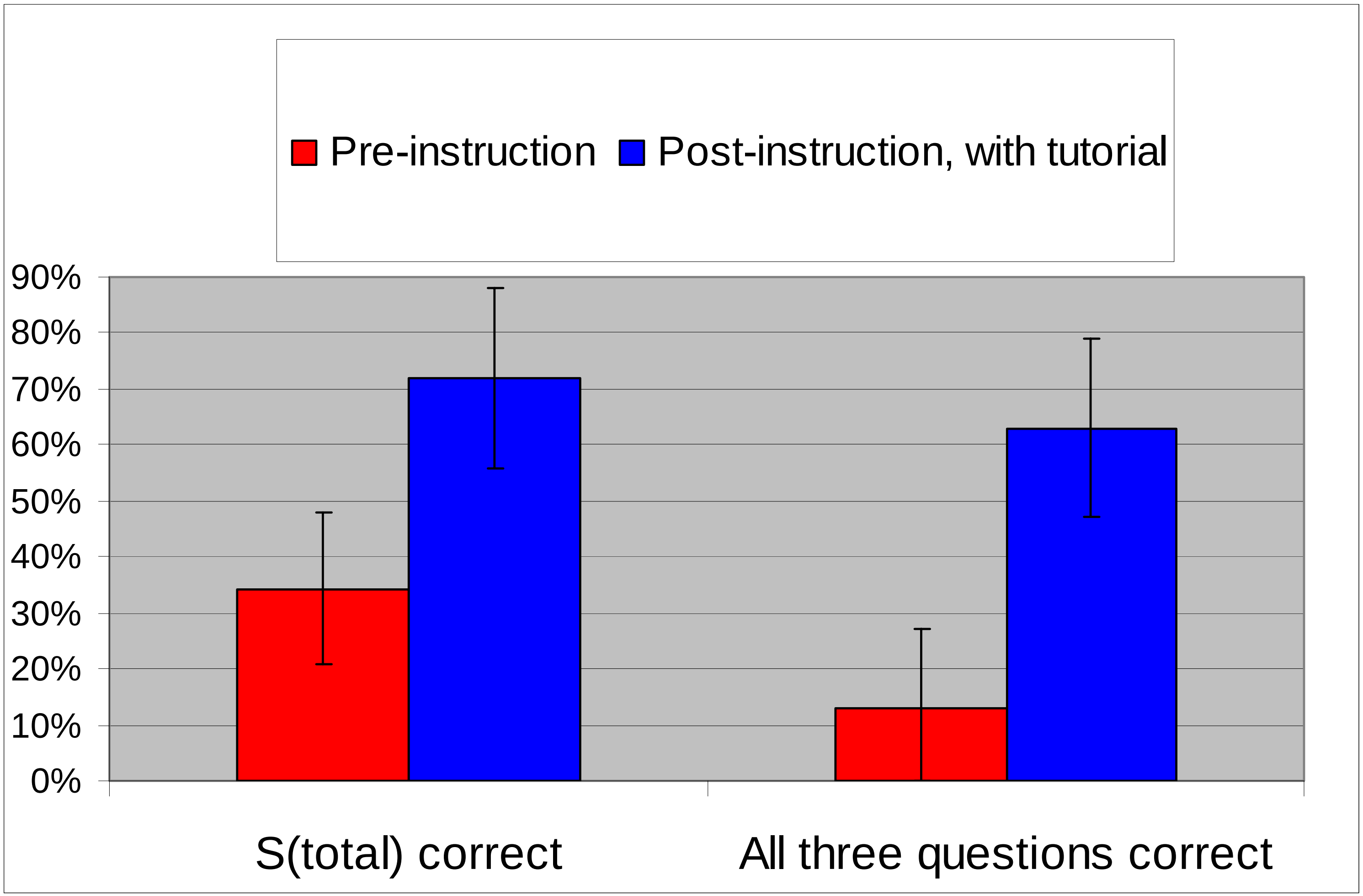
and that definitions of “system” and “surroundings” are arbitrary

Preliminary results are promising…

Responses to Spontaneous-Process Questions
Introductory Students



Responses to Spontaneous-Process Questions
Intermediate Students (*N* = 32, Matched)



Thermodynamics Curricular Materials

- Preliminary versions and initial testing of worksheets for:
  - calorimetry
  - thermochemistry
  - first-law of thermodynamics
  - cyclic processes
  - Carnot cycle
  - entropy
  - free energy

Preliminary testing in general physics and chemistry, and in junior-level thermal physics course

Summary

- Research on student learning lays basis for development of improved instructional materials.

- “Interactive-engagement” instruction using research-based curricula can improve student learning.

- Ongoing development and testing of instructional materials lays the basis for new directions in research, holds promise for sustained improvements in learning.