

# **Improving Instruction through Research on Student Learning: A Perspective from Physics**

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## Collaborators

- Mani Manivannan (Missouri State)
- Tom Greenbowe (Iowa State University, Chemistry)
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- NSF Division of Undergraduate Education
- NSF Division of Physics
- NSF Division of Research, Evaluation, and Communication

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# 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”)*

# Goals of PER

- Improve effectiveness and efficiency of physics instruction
  - guide students to learn concepts in greater depth
- Develop instructional methods and materials that address obstacles which impede learning
- Critically assess and refine instructional innovations

# Methods of PER

- Develop and test diagnostic instruments that assess student understanding
- Probe students' thinking through analysis of written and verbal explanations of their reasoning, supplemented by multiple-choice diagnostics
- Assess learning through measures derived from pre- and post-instruction testing

# 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 Chemistry and Physics [with T. J. Greenbowe]

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. Cochran and P. R. L. Heron, Am. J. Phys. (in press).*

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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).

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[with T. J. Greenbowe]

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

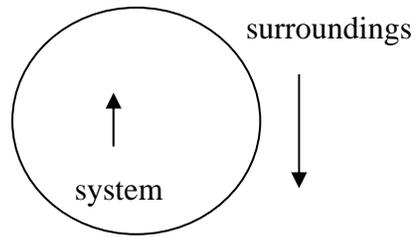
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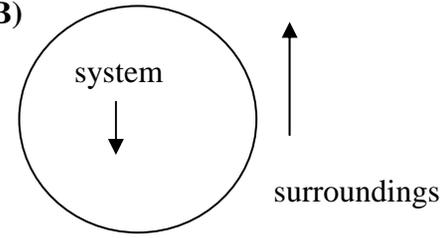
# Student Understanding of Entropy and the Second Law of Thermodynamics in the Context of Chemistry

- 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

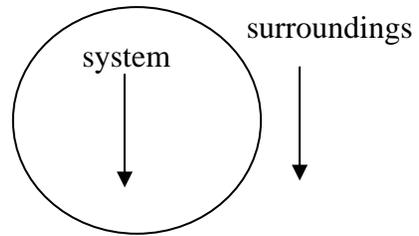
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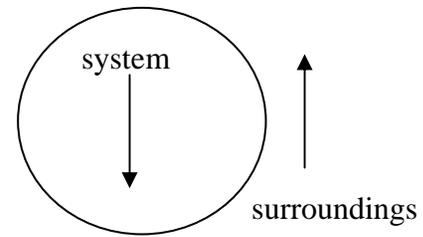
(B)



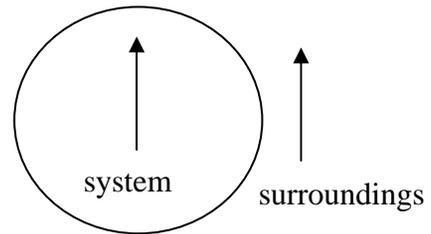
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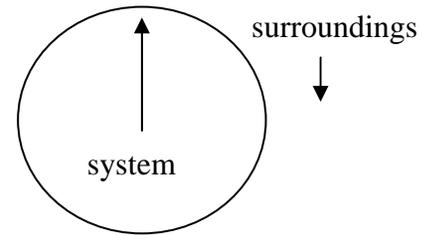
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(E)

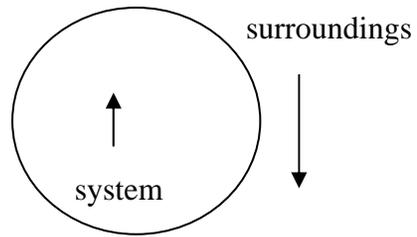


(F)

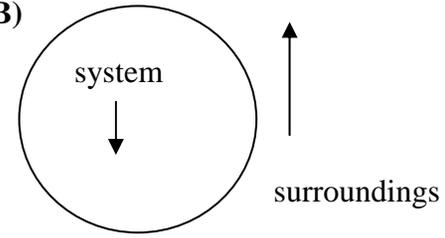


1. The following diagrams represent what happens to the *entropies* of a system (the circle) and its surroundings (everything *outside* the circle) during several different processes. An “up” arrow means the entropy *increases*, a “down” arrow means that it *decreases*. *The length of each arrow is proportional to the absolute value of the entropy change it represents.*
- a) Which of these processes leads to *increasing disorder* of the *system*? (May be more than one.)
  - b) Which of these processes will occur spontaneously? (May be more than one.) Please explain your answers.
  - c) In which of these processes does the Gibbs Free Energy  $G$  of the system *increase*?

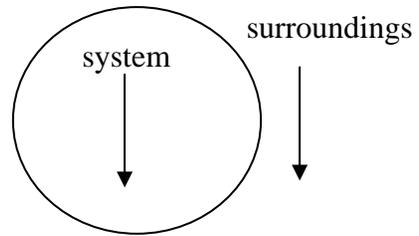
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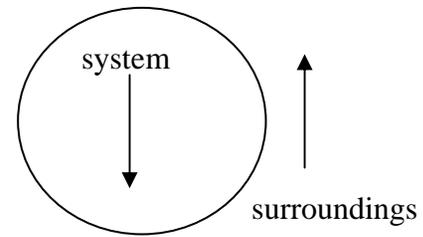
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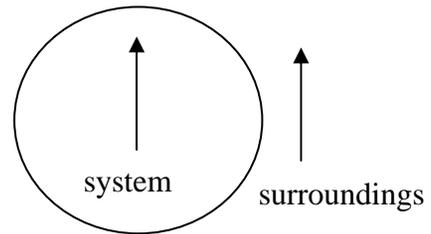
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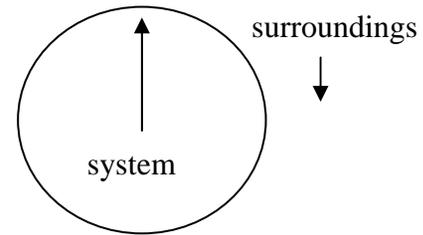
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a) Which of these processes leads to *increasing disorder* of the *system*? (May be more than one.)

**A, E, F (“system” arrow points up)**

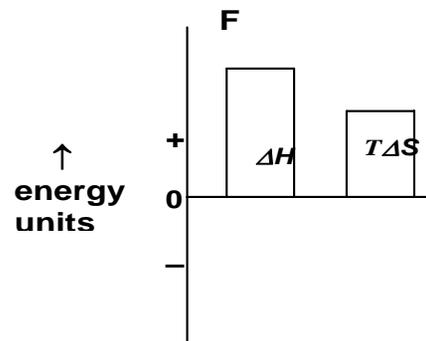
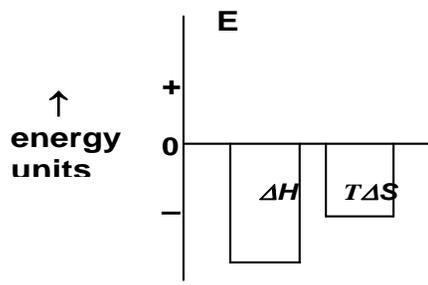
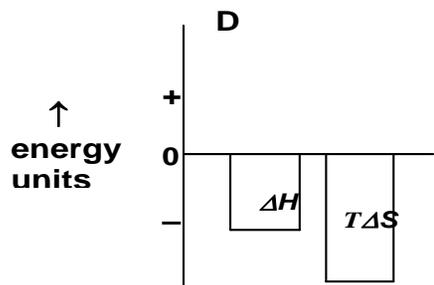
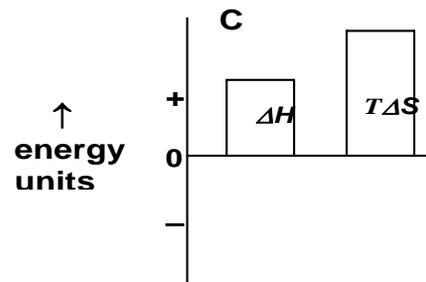
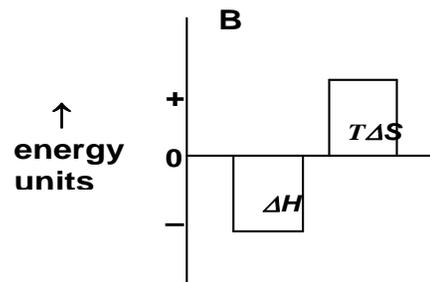
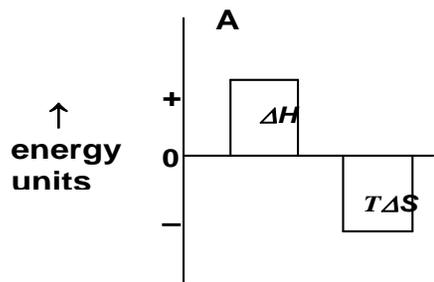
b) Which of these processes will occur spontaneously? (May be more than one.) Please explain your answers.

**B, E, F (“net” arrow points up)**

c) In which of these processes does the Gibbs Free Energy  $G$  of the system *increase*?

**A, C (“net” arrow points down)**  
*[assuming  $T, P$  constant]*

2. These bar charts represent six different processes; in all six, the temperature and the pressure remain *constant*. A bar *above* the horizontal axis indicates a *positive* change (i.e., the quantity *increases* during the process). A bar *below* the horizontal axis indicates a *negative* change (i.e., the quantity *decreases* during the process).



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a) Which of these processes involves the ***largest absorption*** of heat by the system?

b) Which of these processes leads to *increasing disorder* of the system? (May be more than one.) Please explain your answer.

c) Which of these processes will occur spontaneously? (May be more than one.) Explain your answer in each case.

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a) Which of these processes involves the *largest absorption* of heat by the system?

**F (largest positive  $\Delta H$ )**

b) Which of these processes leads to *increasing disorder* of the system? (May be more than one.) Please explain your answer.

**B, C, F (positive values of  $T\Delta S$ )**

c) Which of these processes will occur spontaneously? (May be more than one.) Explain your answer in each case.

**B, C, E ( $\Delta H - T\Delta S < 0$ )**

# 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.*

**Student #2:** I assume that  $\Delta S$  [in the equation  $\Delta G = \Delta H - T\Delta S$ ] is the total entropy of the system and the surroundings.

**Student #3:** “. . . I was just trying to recall whether or not the surroundings have an effect on whether or not it’s spontaneous.”

**Student #6:** “I don’t remember if both the system and surroundings have to be going generally up . . . I don’t know what effect the surroundings have on it.”

# Overall Conceptual Gaps

- There is no recognition of the fact that change in  $G$  of the **system** is directly related to change in  $S$  of the **universe** (= **system** + **surroundings**)
- 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.

# Lack of awareness of constraints and conditions

- There is little recognition that  $\Delta H$  equals *heat absorbed* **only** for constant-pressure processes
- There appears to be no awareness that the requirement that  $\Delta G < 0$  for a spontaneous process only holds for ***constant-pressure, constant-temperature*** processes.

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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 from one reactant to 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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*Thomas J. Greenbowe, Department of Chemistry, Iowa State University of Science and Technology, Ames, IA 50011, USA; e-mail: [tgreenbo@iastate.edu](mailto:tgreenbo@iastate.edu); and David E. Meltzer, Department of Physics and Astronomy, Iowa State University of Science and Technology, Ames, IA 50011, USA; e-mail: [dem@iastate.edu](mailto:dem@iastate.edu)*

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  $\text{Ba}(\text{NO}_3)_2$  solution at  $25.0^\circ\text{C}$  was mixed with 1.00 L of 2.00 M  $\text{Na}_2\text{SO}_4$  solution at  $25.0^\circ\text{C}$ . The final temperature of the solution after mixing was  $31.2^\circ\text{C}$ . Assume that all solutions had a density of 1.00 g/mL and a specific heat of  $4.18 \text{ J/g}\cdot^\circ\text{C}$ .

Calculate the heat of reaction (in kJ).

*Very similar question included on second hour exam*

# Solution to Final Exam Question

$$m = \rho V = (1.00 \text{ g/mL}) (2 \times 10^3 \text{ mL}) = 2 \times 10^3 \text{ g}$$

$$\begin{aligned} q_{\text{soln}} &= mc\Delta T \\ &= (2 \times 10^3 \text{ g}) (4.18 \text{ J/g}^\circ\text{C}) (+6.2^\circ\text{C}) \\ &= +52 \text{ kJ} \end{aligned}$$

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

# 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.

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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.

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# 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. 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

# Some Specific Issues

## ***Many (if not most) students:***

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  - don't use qualitative analysis in problem solving
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"alternative conceptions"—that hinder their understanding of targeted concepts

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.

# Research-Based Curriculum Development

- Investigate student learning with standard instruction; probe learning difficulties
- Develop new materials based on research
- Test and modify materials
- Iterate as needed

# 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

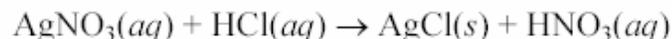
# Thermochemistry Instructional Strategy

*“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 ( $\text{AgNO}_3$ ) 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:



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  $\text{AgNO}_3$  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.

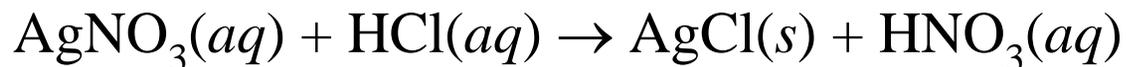
**Lisa:** I don't really think that the heat flows into either of those two. I think heat flows out of both the silver nitrate *and* the hydrochloric acid solution, and that's why the temperature rises.

**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

The textbook (p. 161) describes an experiment in which Silver Nitrate ( $\text{AgNO}_3$ ) solution is mixed with hydrochloric acid ( $\text{HCl}$ ) 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:



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?).

# Excerpt from Worksheet

*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  $\text{AgNO}_3$  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.*

# 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.

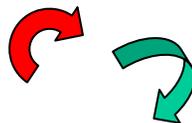
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