

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* **15**, 320-335 (2014)
- Dreyfus, Geller, Meltzer, and Sawtelle, “Resource Letter TTSM-1: Teaching Thermodynamics and Statistical Mechanics in Introductory Physics, Chemistry, and Biology,” *Am. J. Phys.* **83**, 5-21 (2015).

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 (Chandrakha 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
 - $H = E + PV$; $\Delta H =$ 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 identify 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 oversimplification of multi-variable relationships, e.g.:
 - Assume “higher $P \rightarrow$ higher T ” or “higher $T \rightarrow$ 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.

¹Loverude et al., 2002

²Meltzer, 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.

¹Loverude et al., 2002

²Meltzer, 2004

³Meltzer, 2005 [PER Conf. 2004]

⁴Bucy, 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.”

²Meltzer, 2004

⁴Leinonen 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.

¹Loverude et al., 2002

²Meltzer, 2004

³Rozier and Viennot, 1991

⁴Leinonen 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.

¹Loverude et al., 2002

²Meltzer, 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.

¹Sozibilir 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 $\Delta S = \sum Q/T$ 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

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

²Smith, 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

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/>