No, your chocolate is in my peanut butter… Disciplinary barriers in discipline-based education research

Michael Loverude

Dept. of Physics, California State University Fullerton

mloverude@fullerton.edu

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Brief outline

- Introduction
- Probability
- Gas laws
- Concluding remarks

Research on student learning of physics

Some general findings:

- Traditional lecture instruction does not change the way most students respond to conceptual physics questions.
- Quantitative problem solving is typically disconnected from conceptual understanding.
- Student beliefs about learning physics are at odds with those articulated by experts.

The tiniest shred of a theoretical framework

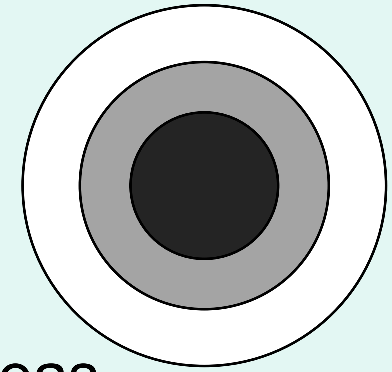
- Traditional lecture teaching seems to be built upon an implicit assumption about learning: knowledge is transmitted from teacher to student, and the student is assumed to be a blank slate

The tiniest shred of a theoretical framework

- PER and its sister disciplines have largely adopted a constructivist model, in which individuals construct their own understanding, and learning involves making connections to and/or reorganizing existing knowledge.

Describing Students' Knowledge Structure

[E. F. Redish, *AJP* (1994), *Teaching Physics* (2003)]



A target, composed of three regions:

Bull's eye: Linked network of things that students know well

Middle ring: Knowledge in development, ideas often incomplete and unstable

Outer ring: Disconnected and fragmentary ideas, dimly understood

It's hard to learn something we don't already almost know, and it's very hard to change an established mental model.

Disciplinary barriers

As noted, there is a lot to gain from interdisciplinary work.

But there are barriers…

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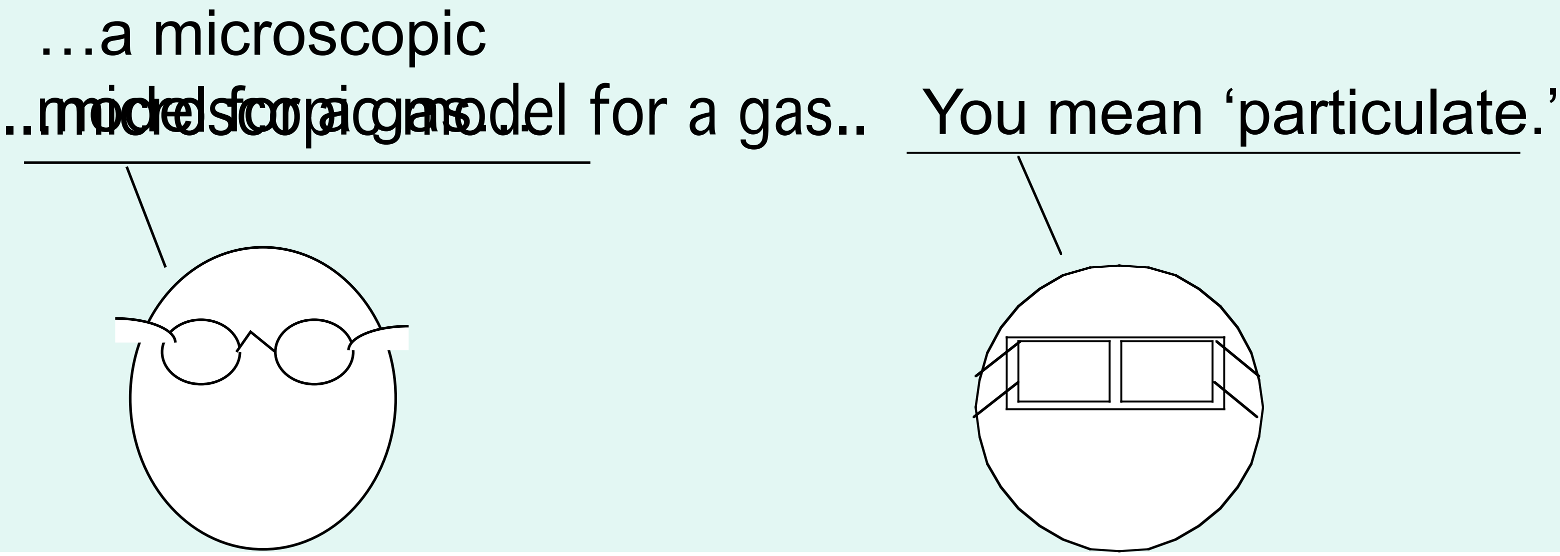

Disciplinary barriers

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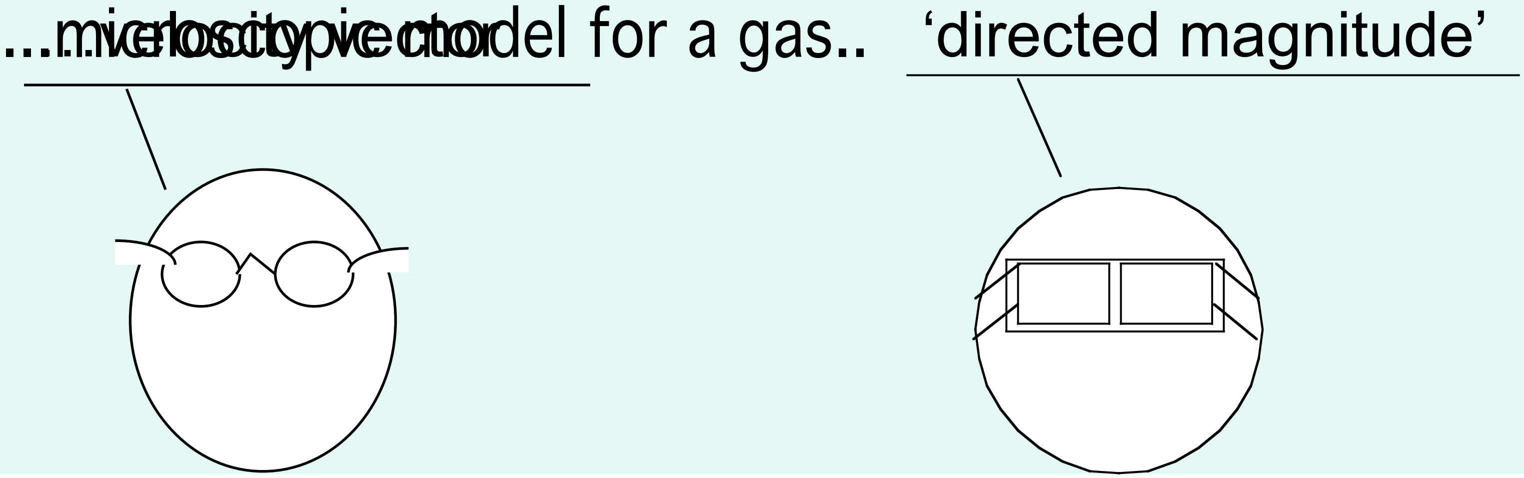

...microscopic model for a gas..

…velocity vector

‘directed magnitude’

Disciplinary barriers

The content of thermal physics is inherently interdisciplinary, touching upon each of the three* fields at the TRUSE conference.

*And don’t forget engineering…

**You could also include statistics, if you believe statistics is different from math.

Disciplinary barriers

Previous and ongoing work by collaborators that crosses these barriers:

State functions, entropy, etc. - DMe, WC
Integrals in thermodynamics and math - JRT
Partial derivatives in thermodynamics - BB, NB
Slope and derivative in physics and math - WC
Density of states, normal distribution - DMt
Boltzmann factor, Taylor series - TS

Two collaborations

CCLI project “Learning and teaching of thermal physics”
PIs: Loverude, Meltzer, Thompson

- Develop a series of tutorial exercises for upper-division thermal physics
- Perform PER to document student understanding of target concepts and effectiveness of curriculum

Collaborative project “Student understanding of particulate phenomena in chemistry and physics courses”
Monteyne, Loverude, Gonzalez

- Examine student understanding of particulate models of matter in various physics and chemistry contexts
- Probe student ability to match particulate-level phenomena to macroscopic behavior and properties

Disciplinary barriers

Our courses often assume prior knowledge*** from pre-requisite courses*, some from other fields.**

*But my students take courses out of sequence.

**And those other departments do things… differently.

***Also, many years of research call into question what students get from prerequisite courses.

Brief outline

- Introduction
- Probability
- Gas laws
- Concluding remarks

Context for investigation

Courses at Cal State Fullerton (CSUF)

- Thermal Physics (Physics 310)

Physics core course, required for majors / minors

Covers thermodynamics, statistical physics, in the ‘hybrid’ thermal physics approach (Schroeder, *Thermal Physics*).

2 75-minute meetings per week

Lecture course nominally, but enrollments small (6 - 19)

For many students, this course is the first physics course covering thermal physics, which is not part of the intro course at CSUF.

About one in six have taken a college math course covering probability and statistics.

Context for investigation

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2 75-minute meetings per week

Lecture course nominally, but enrollments small (6 - 19)

Student abilities and backgrounds vary considerably,
with sophomores to seniors (or post-baccs!).

The instructor is very close to the research project.

One must be very careful about generalizations.

Motivation

In course text, Second Law of Thermodynamics arises naturally from a sequence based on the analysis of the statistical behavior of matter.

- Mathematics of coin flips, $\Omega = \dfrac{N!}{H!(N-H)!}$
- All allowed microstates are equally probable;
  Probability of a macrostate is thus proportional to multiplicity, or number of microstates for that macrostate

- Multiplicity in the Einstein model of a solid
- Interacting Einstein solids:
  Macroscopic equilibrium ⇔ maximum multiplicity
- For large systems, probability distribution sharply peaked, so evolution to equilibrium is a statistical phenomenon

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  Macroscopic equilibrium ←→ maximum multiplicity
- For large systems, probability distribution sharply peaked, so evolution to equilibrium is a statistical phenomenon

Coin flip question

Problem Statement: Assume that you flip six fair coins. (Fair coins have an equal chance of flipping heads and tails.)

- What is the most likely number of heads?
- How likely is it that you will flip exactly 6 heads?
- Is the probability of exactly 5 heads *greater than*, *less than*, or *equal to* the probability of flipping exactly six heads?

Problem posed in seven sections of Thermal Physics course ($N = 65$), *before tutorial instruction and homework on probability and statistics, but after assigned reading and some introductory lecture.*

Coin flip question

Problem Statement: Assume that you flip six fair coins. (Fair coins have an equal chance of flipping heads and tails.)

- How likely is it that you will flip exactly 6 heads?

Just over half the students correctly determined P = $(.5)^6$.

Some had difficulty calculating the numerical value.
"1/2 x 1/2 x 1/2 x 1/2 x 1/2 x 1/2 = 1 / 12."

About 40% of students gave wrong answers.
"6 / 12 = 1/2"
"1 / 7 Based on the …7 states"   [macrostates?]

Coin flip question

Is the probability of flipping exactly 5 heads *greater than, less than,* or *equal to* the probability of flipping exactly six heads? If the probabilities are different, try to quantify how different they are (eg show a ratio…how many times greater?). Explain.

There is one ***microstate*** *with exactly six heads: HHHHHH.*
P = 1 / 64 ~ 1.6%

There are six ***microstates*** *with exactly five heads: HHHHHT, HHHHTH, HHHTHH, HHTHHH, HTHHHH, THHHHH.*
P = 6 / 64 ~ 10%

Thus the probability of exactly five heads is six times that of exactly six heads.

Coin flip question

Is the probability of flipping exactly 5 heads *greater than, less than,* or *equal to* the probability of flipping exactly six heads? If the probabilities are different, try to quantify how different they are (eg show a ratio…how many times greater?). Explain.

Correct with or without explanation:	*~30%*
Greater but with incorrect ratios:	*35%*

- *"P(5 heads) = $(.5)^5 > (.5)^6$; twice as likely"*
- *"1 / 5 > 1 / 6"*

Equal:	*20%*

Enhanced coin flip question

Problem Statement:

(Fair coins have an equal chance of flipping heads and tails.)

Is the probability of flipping six fair coins and getting exactly 1 head *greater than*, *less than*, or *equal to* the probability of flipping 600 fair coins and getting exactly 100 heads? Explain.

Enhanced coin flip question

Problem Statement:

(Fair coins have an equal chance of flipping heads and tails.)

Is the probability of flipping six fair coins and getting exactly 1 head *greater than*, *less than*, or *equal to* the probability of flipping 600 fair coins and getting exactly 100 heads? Explain.

$$P\,(1\ \text{head},\ 6\ \text{coins}) = 6/64 \sim 10^{-1}$$

$$P\,(100\ \text{heads},\ 600\ \text{coins}) = \frac{600!}{100!500!}\frac{1}{2^{600}} \sim 10^{-65}$$

Enhanced coin flip question

Problem Statement:

(Fair coins have an equal chance of flipping heads and tails.)

Is the probability of flipping six fair coins and getting exactly 1 head *greater than*, *less than*, or *equal to* the probability of flipping 600 fair coins and getting exactly 100 heads? Explain.

Six sections of Thermal Physics (N = 60)

30% correct (about half w/correct explanations).
70% said the probabilities will be equal.
"In both cases it is 1/6 of the number of flips."

Student intuition is very strongly at odds with the math.

This sequence seemed to be a useful probe of student thinking.

However, I finally thought to look in the literature of other fields.

"Many research studies have shown that ideas of probability and statistics are very difficult for students to learn and often conflict with many of their own beliefs and intuitions about data and chance (Shaughnessy, 1992; Garfield & Ahlgren, 1988)." -- Garfield, *Int. Stat. Rvw.* 63 (1995).

Six children question

Imagine that all families of six children in a certain area were surveyed. In 72 families the *exact order* of births of boys and girls was G B G B B G. What is your estimate of the number of families surveyed in which the *exact order* of births was B G B B B B? If you are unable to make a quantitative estimate, state whether it is *greater than, less than,* or *equal to* 72.

(See Konold, *Journal of Statistics Education* 3, 1995, and ultimately Kahneman* & Tversky, *Cognitive Psychology* 2, 1972.)

*Nobel Prize in Economics in 2002.

Six children question

Imagine that all families of six children in a certain area were surveyed. In 72 families the *exact order* of births of boys and girls was G B G B B G. What is your estimate of the number of families surveyed in which the *exact order* of births was B G B B B B? If you are unable to make a quantitative estimate, state whether it is *greater than*, *less than*, or *equal to* 72.

Assuming that boys and girls are equally likely, the two sequences are equally probable. Thus the best estimate is 72.

In physics terms, the microstates are equally probable even though the macrostates to which they correspond ('3 girls, 3 boys' and '1 girl, 5 boys') are not.

Six children question

Imagine that all families of six children in a certain area were surveyed. In 72 families the *exact order* of births of boys and girls was G B G B B G. What is your estimate of the number of families surveyed in which the *exact order* of births was B G B B B B? If you are unable to make a quantitative estimate, state whether it is *greater than*, *less than*, or *equal to* 72.

In four sections of Thermal Physics (N = 40), after relevant lecture instruction:

~40% correct answers

~40% predicted BGBBBB less probable
"It's more likely to get 3 G & 3 B than 1 G & 5 B."

Six children question

"It's more likely to get 3 G & 3 B than 1 G & 5 B."

Kahneman & Tversky described this type of response as reflecting the 'representativeness heuristic,' a simple and often useful rule that is perhaps hard-wired in the human brain.

In the context of statistical physics, incorrect answers reflect a difficulty in distinguishing between macrostate and microstate. This difficulty may influence student responses in contexts throughout the course.

Addressing student difficulties

An important goal of PER is to improve instruction through cumulative, incremental change by:

- conducting research to identify and address student difficulties
- developing research-based instructional materials

Addressing student difficulties

Tutorials (“Washington-style”) are a means of inserting small group guided-inquiry activities into a lecture course (typically in sections for larger courses).

Small groups (2-4) work through carefully structured worksheets while the instructor questions students

Emphasis is on:

- constructing concepts, addressing student difficulties
- developing reasoning ability
- relating physics formalism to the real world

but *not* on:

- solving standard (quantitative) textbook problems

Addressing student difficulties

Tutorials developed or modified as part of current project:

- *Ideal Gas Law*
- *Particulate Model of a Gas*
- *First Law of Thermodynamics*
- *Enthalpy*
- *Counting Microstates*
- *Counting States in the Einstein Solid*
- *Approach to Thermal Equilibrium*
- *Entropy Changes in Ideal Gas Processes*
- *Engines and Refrigerators*
- *Phase Diagrams*
- *Maxwell Relations and Legendre Transforms*
- *Boltzmann Factor and Partition Function*

Addressing student difficulties

Questions posed on exam (N = 18) after tutorial sequence including *Counting Microstates*

Midterm Exam: Assume fair coins. Determine the probability of the following outcomes:

- 6 flips, exactly 3 heads (88% correct)
- HHHHHHHTTT (50% correct)

Addressing student difficulties

For Spring 2010, additional homework exercises added to *Counting States* tutorial:

For each of the following descriptions, state whether the description corresponds to a microstate or a macrostate. Explain briefly.

- One coin is flipped seven times, the first three are heads and the others are tails.
- Seven distinguishable coins are flipped, resulting in three tails and four heads.
- etc.

Rank the probabilities of the four states.

Addressing student difficulties

Questions posed on exam (N = 14) after tutorial sequence including *Counting Microstates* + *revised HW*

Midterm Exam: Assume fair coins. Determine the probability of the following outcomes:

• 6 flips, exactly 3 heads	(88% correct) 86% correct
•HHHHHHHTTT	(50% correct) 71% correct

Summary

- Many answers given by advanced students do not reflect useful or correct intuition about probability, consistent with prior work with less expert students.
- Students need help with what instructors assume are simple calculations and time to build their intuition. (The course text has under three pages on coin flipping before moving to the Einstein solid.)
- Tutorial instruction can help, but some students still need help distinguishing micro- and macrostates. An iterative approach based on continuing assessment of student learning is needed.

Brief outline

- Introduction
- Probability
- Gas laws
- Concluding remarks

Context for investigation

Courses at Cal State Fullerton (CSUF)

- Thermal Physics (Physics 310)
- Physical Chemistry (Chem 371A-B)

Chemistry core course, required for majors

Covers thermodynamics (first semester), quantum mechanics (second semester) (Atkins, *Physical Chemistry*).

2 75-minute meetings per week

Lecture course nominally, but enrollments small (15-30)

Course prerequisites and levels are similar, but many believe that departmental cultures, instructional traditions are very different.

Questions for research

To what extent to students in these courses have a deep understanding of thermo topics normally covered in first year courses?

- Ideal gas law
- Particulate models for a gas
- First law of thermodynamics, heat / work / internal energy

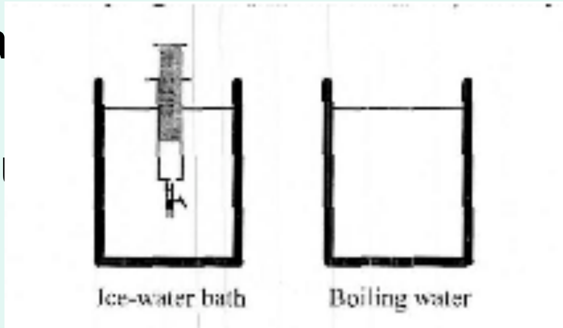
Are there differences in response patterns between the two student populations?

Ideal gas pretest*

*Kautz et al., 2005.

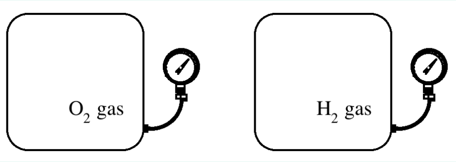
Problems:

Vertical syringe with movable frictionless piston of ma
M, sealed so no gas may enter or leave. Cylinder is
placed in a beaker of boiling water, comes to equilibri



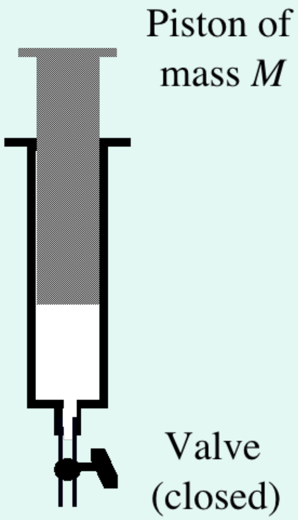
Compare P, V of gas before and after

Two identical tanks contain ideal gas, oxygen and hydrogen. Pressure gauges read the same, both tanks in equilibrium with room.



Compare number of moles in the tanks

Syringe problem*



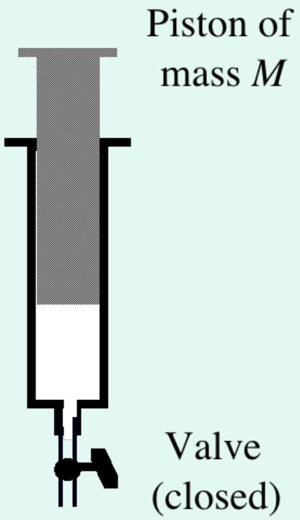
<u>Expected answers:</u>

State whether the following quantities are greater than, less than, or equal to their initial values:

the pressure of the gas: *equal to*

The upward force by gas inside equals sum of downward force by gas outside and gravitational force; $P = P_{\text{atm}} + Mg/A$

Syringe problem*



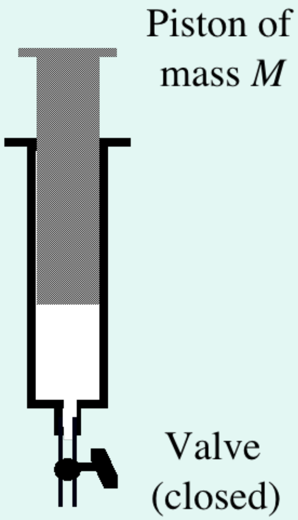
<u>Expected answers:</u>
State whether the following quantities are greater than, less than, or equal to their initial values:

the pressure of the gas: *equal to*
the volume of the gas: *greater than*

Apply the ideal gas law: $PV = nRT$.

Pressure is the same, number of moles is the same, T is greater, so V must be greater.

Syringe problem*



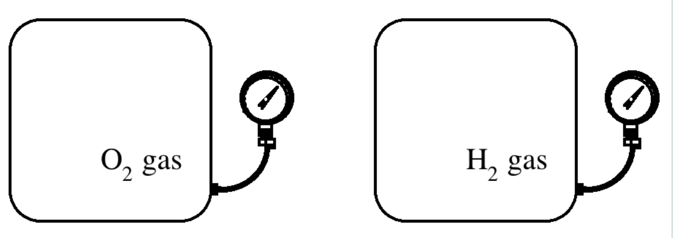
Expected answers:
State whether the following quantities are greater than, less than, or equal to their initial values:

the pressure of the gas: *equal to*

	CSUF PHYS310 (*N* = 43)	CSUF CHEM371A (*N* = 24)
Correct	40%	20%
P increases	58%	80%

Two-container question

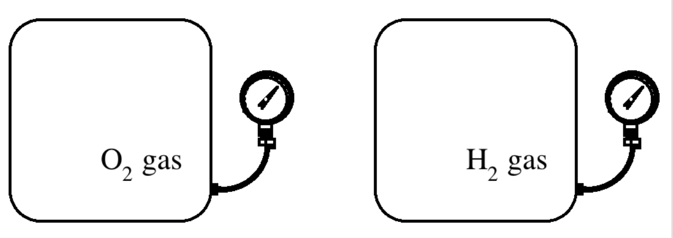
- Two tanks, same size and shape
- Left tank contains O_2, right tank H_2; treat both gases as ideal.
- Gases in the containers are at the same temperature, pressure.



Is the number of oxygen molecules in the left container *greater than, less than,* or *equal to* the number of hydrogen molecules in the right container? Explain your reasoning.

(From Kautz, et al., 2005.)

Two-container question

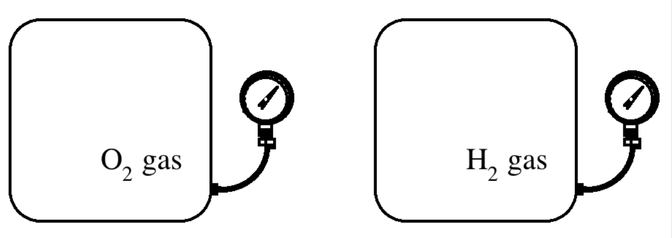


Is the number of oxygen molecules in the left container *greater than, less than,* or *equal to* the number of hydrogen molecules in the right container? Explain your reasoning.

"The number of hydrogen molecules is greater than that of the nitrogen molecules. The hydrogen molecules have less mass and thus exert less force than the nitrogen, and there must [be] more molecules to equal the force of the nitrogen."

Two-container question

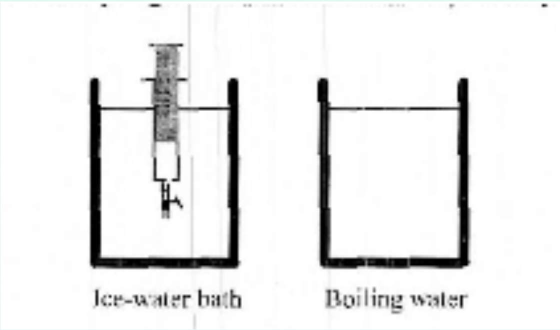
Is the number of oxygen molecules in the left container *greater than, less than,* or *equal to* the number of hydrogen molecules in the right container? Explain your reasoning.

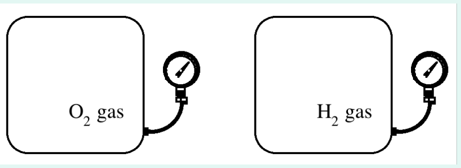


	CSUF PHYS310 (*N* = 43)	CSUF CHEM371A (*N* = 24)
Correct	51%	42%
$N_{left} < N_{right}$	47%	50%

Ideal gas pretest*

In problems posed in lower-level courses at CSUF, students in Chemistry courses seemed more likely to refer to particulate-level phenomena in their explanations,* but there was no strong signal here.





*Monteyne, Loverude, Gonzalez, AIP Conference Proceedings 1064 (2008).

Gas reaction question

In this problem, assume that all gas volumes are measured at a temperature 320 K and pressure 120 kPa (i.e., the product(s) of the reaction as well as the reactants).

The gases H_2 and O_2 react to form water vapor, H_2O. The chemical equation that describes this reaction is
$2\ H_2\ (g) + O_2\ (g) \text{-->}\ 2\ H_2O\ (g)$.

Suppose that 600.0 ml of H_2 take part in a reaction with O_2.

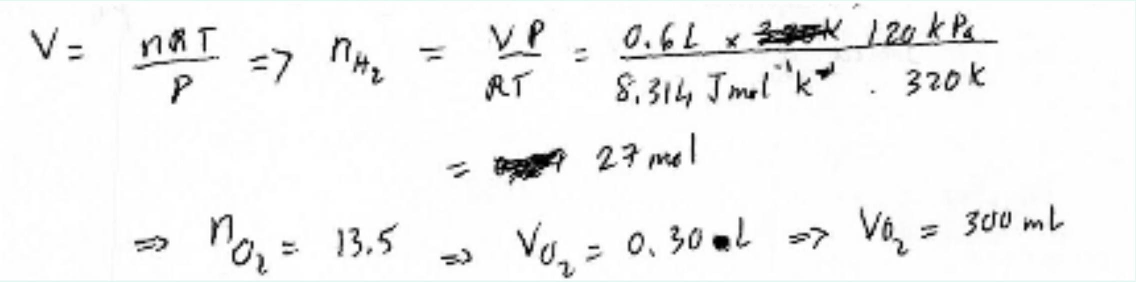
1. What is the volume of O_2 needed? (You should be able to find a numerical answer.)
2. What is the volume of the H_2O produced?

Gas reaction question

$2\,H_2\,(g) + O_2\,(g) \rightarrow 2\,H_2O\,(g)$.

Suppose that 600.0 ml of H_2 take part in a reaction with O_2.

1. What is the volume of O_2 needed? (You should be able to find a numerical answer.)

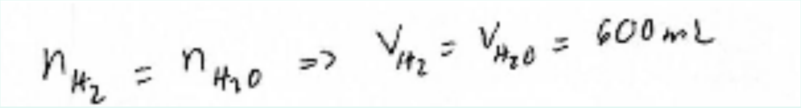


$$V = \frac{nRT}{P} \Rightarrow n_{H_2} = \frac{VP}{RT} = \frac{0.6\,L \times \cancel{300\,K}\ 120\,kPa}{8.314\,J\,mol^{-1}\,K^{-1} \cdot 320\,K}$$

$$= [illegible]\ 27\,mol$$

$$\Rightarrow n_{O_2} = 13.5 \Rightarrow V_{O_2} = 0.30\,L \Rightarrow V_{O_2} = 300\,mL$$

2. What is the volume of the H_2O produced?



$$n_{H_2} = n_{H_2O} \Rightarrow V_{H_2} = V_{H_2O} = 600\,mL$$

Gas reaction question

The gases H_2 and O_2 react to form water vapor, H_2O. The chemical equation that describes this reaction is
$2\ H_2\ (g) + O_2\ (g) \rightarrow 2\ H_2O\ (g)$. 600.0 ml of H_2 take part in a reaction with O_2.

2. What is the volume of the H_2O produced?

	Phys 310 (*N* = 10)	Chem 371A (*N* = 24)
Correct*	40%	50%
Added volumes	20%	10%

Chemistry vs. Physics

Response patterns on identical questions can be quite different, and not just in one direction.

Free expansion: Is W positive, negative, zero?

Show that $T\left(\frac{\partial P}{\partial T}\right)_V - P$ = 0 for an ideal gas.

Phys310: 10 / 18 correct
Chem371: 24 / 26 correct

Phys310: 12 / 18 correct
Chem371: 8 / 26 correct

An Opportunity

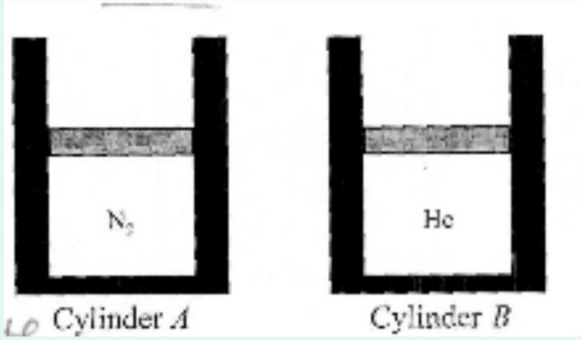
In Fall 2008, we were able to test some tutorials developed by MEL in a section of Chem 371A, including:

- Ideal gas law
- First law of thermodynamics
- Enthalpy
- Entropy
- Phase Diagrams

Is there any hope of curricular innovations crossing the bright shining lines between disciplines?

Two cylinders problem

Post-test for *Ideal Gas Law* tutorial



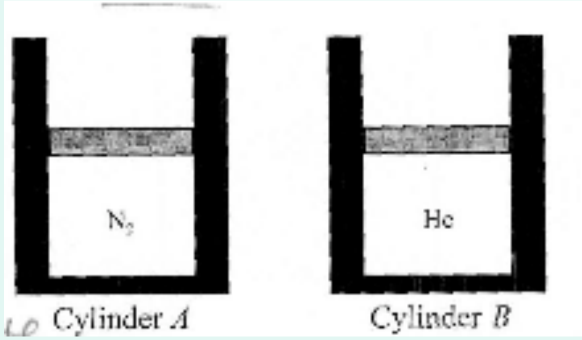
Problem statement: Identical cylinders, pistons, unknown quantities of (ideal) gases, both in equilibrium with room

Compare numbers of moles.

	Chem 371A (*N* = 24)	Phys 310 (*N* = 19)
Correct*	96%	94%
More Helium	4%	6%

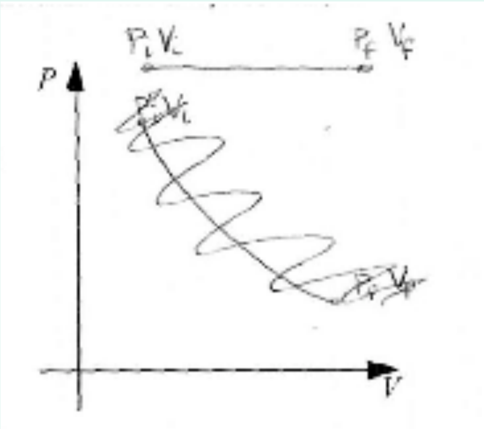
Two cylinders problem

Post-test for *Ideal Gas Law* tutorial



Problem statement: Cylinder A placed in contact with cool water bath, slowly reaches equilibrium. Sketch process on PV diagram.

	Chem 371A (*N* = 24)	Phys 310 (*N* = 19)
Correct*	46%	84%
Other	54%	16%



Summary

- Students in both upper-division courses enter the course still having difficulty with concepts that many instructors would consider prerequisites from intro-level courses.

- On many questions response patterns are very similar in the two courses, but there are some differences that are not easily explained as yet. Do different disciplinary traditions and instructional programs really make students think differently?

- Instructional materials designed in the context of the physics course can benefit both groups, though some issues remain.

Brief outline

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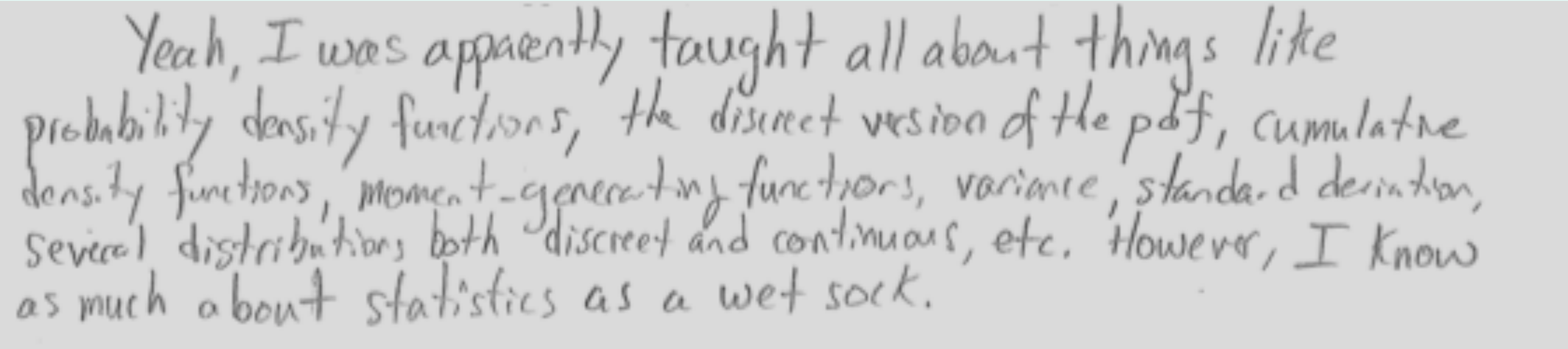

Yeah, I was apparently taught all about things like probability density functions, the discreet version of the pdf, cumulative density functions, moment-generating functions, variance, standard deviation, several distributions both discreet and continuous, etc. However, I know as much about statistics as a wet sock.

Disciplinary barriers

I believe it’s important, and productive, to cross these disciplinary barriers whenever possible.

It’s not easy (F vs. A? Directed magnitude?), but it can be very fruitful.

Thanks to JT, MT, CR, WC!