Rethinking College Physics

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Outline

- 1. The Need and the Opportunity
- 2. The Course and the Population
- 3. What Do We Have to Offer?
- 4. Thinking About Thinking
- 5. "Learning to Learn Science"
- 6. Evaluating the Results
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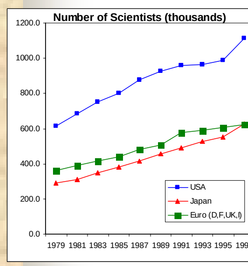
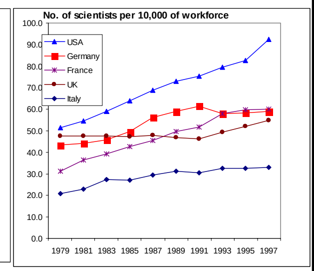
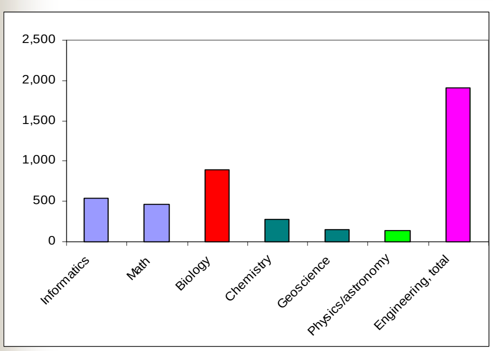
1. The Need and the Opportunity

The total number of scientists continues to grow — both in total numbers and as a fraction of the workforce.





US Scientists by field 1997 (thousands)



An Opportunity?

- The growth of science and the need for educating a larger population in science offers a tremendous opportunity for physics educators.
- After all, isn't physics the best place to start really learning what science is about and how to do it?

2. The Course and the Population

Algebra-Based Physics: The Course

- Eventually, we might want to rethink our offerings for biologists (joint major, 3-term course with modern physics) but let's begin by working within current boundary conditions.
- Environment (two 14 week semesters)
  - Lecture (150 minutes / week)
  - Recitation (50 minutes / week)
  - Lab (110 minutes / week)
  - Partially graded homework each week

Algebra-Based Physics: The Population

- Population Characteristics
  - Predominantly female. (~60%)
  - Completed two semesters of calculus (>95%) but less confident about math than engineers.
  - Mostly biological science majors. (~75%) (The college of life sciences requires physics.)
  - Not all pre-meds. (~30-40%)
  - Often juniors and seniors. (~75%)
  - Research oriented (~75%)

3. What do we have to offer?

Physics is an excellent place to learn the "3 Ms"

- *Mechanism:* Physics is a particularly good place to learn to think in "physical models" – in terms of systems of objects with particular properties and interactions leading to explanations of complex behavior.
- *Mathematics:* Physics can help students build an understanding of the role of mathematics as a language
  - for expressing relationships
  - to generating predictions.
  - to organize conceptual knowledge
- *Measurement*: Physics can help students understand the nature and limitations of measurement and how to interpret data.

...in Principle!

However…

- Traditionally, even physics majors learn little in their first college physics course.
- They develop a solid understanding of the material through repetition from different angles and from eventually teaching it.
- Other scientists and engineers may only take one year of university physics.
  - *Is the 1st step in a multi-step process of significant value for students in other sciences?*
  - *How much of value can be accomplished in a one year course?*

4. Thinking about thinking

Understanding our students

- To understand
  - what we have to offer
  - why what we traditionally offer only has limited success

we need to treat the problem of teaching and learning in the same way we do any research problem: using

- observation
- analysis
- modeling

Build on what's known. Select what's relevant and robust.

- Seek general principles (heuristics) to help understand what we see in our classes and in our research.
- *Triangulate*:
  Look for ideas consistent with data from
  - Phenomenological observations – real people in real environments: classrooms (*Education research*)
  - Idealized ("zero friction") experiments to probe fundamental mechanisms (*Cognitive science*)
  - Studies of mechanisms in the brain for plausibility (*Neuroscience*)

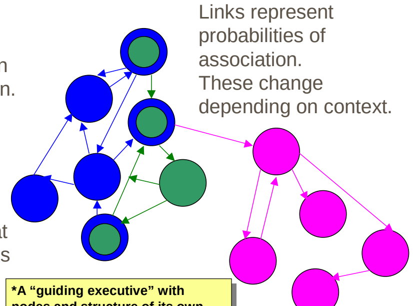
A model of thinking relevant to instruction:

- Long-term memory can exist in (at least) 3 stages of activation
  - inactive,
  - primed (ready for use),
  - active (immediately accessible)
- Memory is associative and productive
  - Activating one element leads (with some probability) to the activation of associated elements.
- Activation and association are context dependent
  - What is activated and subsequent activations depend on the context, both external and internal (other activated elements).

**Joaquin Fuster, Memory in the Cerebral Cortex: An Empirical Approach to Neural Networks in the Human and Nonhuman Primate (MIT Press, 1999).*

Organization of Long-Term Memory:

This picture is an oversimplification. "Nodes" have structure in multiple dimensions. There are "metanodes" that control what links appear when.*

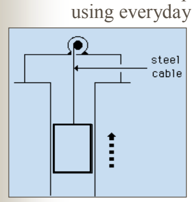


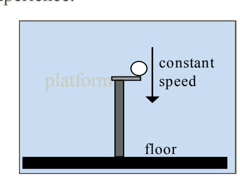
Links represent probabilities of association. These change depending on context.

***A "guiding executive" with nodes and structure of its own – epistemology, control, affect, etc.**

Example: Context Dependence

- Students in engineering physics were asked two equivalent questions on Newton's first law.
  - one question was phrased in physics terms using a laboratory example
  - the other was phrased in common speech using everyday experience.





Results

- On the physics-like problem
  - 90% give the correct answer
    - the normal force on the ball is equal to the downward force due to gravity
- On the everyday problem
  - 54% choose the correct answer:
    - the upward force on the elevator by the cables equals the downward force due to gravity
  - 36% choose a common misconception:
    - the upward force on the elevator by the cables is greater than the downward force due to gravity

R. N. Steinberg and M. S. Sabella, Phys. Teach. 35, 150-155 (1997).

It's not just knowledge

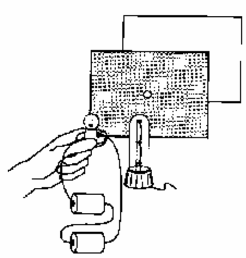
- Students' understanding of the nature of scientific knowledge in general and what is happening in a physics course in particular may not agree with what we want and expect.
- "Science is not supposed to make sense."
  - Students in a laboratory in which they tried to create ways of thinking about electric current using models such as traffic flow and water.

- S1: Are you going to tell us at some point what electricity <u>really</u> does?
- TA 1: In lecture, I think tomorrow, he'll give some idea of a model that we're going to use in class that works.
- TA 2: So no, not really.
- TA 1: It'll be similar in a lot of ways [to what we've done here].
- S1: But this… I still have no idea how electricity … works … and if he's just going to give us another model tomorrow, I still won't know what electricity does.

- TA 2: OK. So this is what we're going to learn about physics. What stuff "really" does is sort of irrelevant, right? Cause it doesn't matter… [if it] always works to tell you whether or not a light bulb's going to light, that's good enough.
- TA 1: We're interested in knowing how to make predictions.
- S1: You aren't interested in what <u>really is</u> though?
- TA 2: No. The philosophy majors can do that…. I mean, would you guys feel better if I used words you didn't understand?
- S1: That's what I'm used to!

"In physics class I don't need to understand what it means."

- Students in a tutorial in which they are analyzing light going through a hole to build the ray model of light (the idea that light travels in straigh lines).



Expectations

- For each activity we give them, students bring not only general expectations about physics, but specific expectations about "What is it we're doing here?"
- These context-dependent expectations have cognates in different fields.
  - Frames (rhetoric)
  - Scripts (cognitive psychology)
  - Registers (sociolinguistics)
  - Epistemic games (education)

Implications of the Model

- Students can recognize and replay something they've seen but not know how to use it.
- Students' thinking can be inconsistent.
- Students may not know what understanding something means.
- Students may not know what we expect them to do to learn something.

Messages

- If we are to help students learn these more general issues we have to not only be concerned with
  - what our instruction presents about content (the "overt message")

but also on
  - what our instruction is saying about how it's appropriate to work with and think about the content (the "covert message")

5. "Learning to Learn Science"

Learning How to Learn Science: Physics for bioscience majors

- Funded by NSF-ROLE (Research on Learning in Education)
- Supports
  - research into "learning how to learn"
  - development of learning environments to help foster this in College Physics

The UMd PERG:

- **Faculty**
  - David Hammer* (Ph / C&I)
  - Joe Redish* (Ph)
  - Emily van Zee (C&I)
- **Grad Students**
  - Rebecca Lippmann* (Ph)
  - Jon Tuminaro* (Ph)
  - Leslie Atkins (Ph)
  - Tim McCaskey* (Ph)
  - Paul Gresser* (Ph)
  - Ray Hodges* (Ph)
  - Rosemary Russ* (Ph)
  - Loucas Louca (C&I)
  - Paul Hutchinson (C&I)
- **Postdocs**
  - Andy Elby* (Ph / C&I)
  - Laura Lising* (Ph / C&I)
  - Rachel Scherr* (Ph)
  - David May* (C&I)
- **Undergraduates**
  - Leila Malieri* (Ph)
  - Scott Snowman* (Ph / C&I)
  - Nora McDermott-Taboori* (Ph) (Vassar summer '01)
  - Kara Gray* (Ph) (Kansas State summer '02)

* Participants in LtLPh

Physics
Curriculum & Instruction
Both

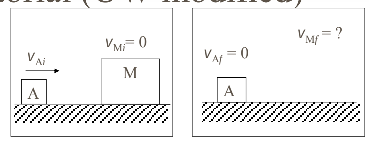
Changes to the learning environment

- Lecture
  - in-class interactions with Personal Response System
  - enhanced ILDs
  - linking to personal experience
  - focus on problem solving using core (conceptual) equations
  - use of "Elby pairs"
- Homework
  - fewer, harder, thinking problems
  - epistemological essay questions
  - estimation (Fermi) problems
  - context relevant problems
  - "Course Center" office hours
- Laboratory
  - "Scientific Community Labs"
  - no lab manual
  - exploratory or guided discovery labs
  - measurement as rhetoric (convincing someone else)
- Tutorial
  - mix of UW-PEG and ABP Tutorials
  - coordinated with lab and ILDs

Goal: Mathematics as Sense Making

- Our observations of students attempting to reason mathematically suggest that student failure to use math appropriately is – at least in part – due to a failure to map conceptual meaning onto mathematics, not solely to lack of skill in formal manipulations. (J. Tuminaro)

Tutorial (UW modified)



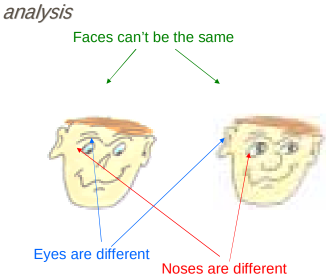
The mass of glider A is one-half that of glider M (i.e. $m_M = 2m_A$).

Apply Newton's second law ($F_{net} = m\Delta v/\Delta t$) to each of the colliding gliders in Experiment 1 to compare the *change in momentum* ($\Delta p = m\Delta v$) of gliders A and M during the collision. Discuss both magnitude and direction. Explain.

- In a videotaped discussion a student writes down momentum conservation and Newton's third law and her equations are correct and yield the correct conclusion: the changes in momenta are equal (and opposite).
- But she then continues…

S1: "So the momentums got to be the same right?"
…
S1: "No, this is not right."
…
S1: "But the change in velocities are not the same, though…that's the problem, I was thinking [the changes in velocity] were the same."
…
S1: "How could [the momenta] be the same? If the masses are different and the change in velocities are different the momentums *can't* be the same."

- She throws away her correct mathematically generated conclusion, and replaces it by common sense reasoning – a *feature analysis*



Covert message 1: Equations can carry conceptual meaning.

- We minimize applying equations without thinking.
- We focus on using a few equations that have clear conceptual content and ask them to derive results and interpret their meaning.
- It sends a different covert message
  - not: "physics (and science) is about lots of independent facts and reasoning can be automated." ("Science as state capitals")
  - rather, "physics is about making sense of the physical world."

Conceptual Equations

- Kinematics are handled with only two equations.
- These equations are related directly to the conceptual ideas.
- Other equations are (in lecture) obtained from processing these equations.
- If students put in numbers early, intermediate variables appear, but not the traditional equations (e.g., $s = \frac{1}{2} at^2$)

$$\langle v \rangle = \frac{\Delta x}{\Delta t}$$

$$\langle a \rangle = \frac{\Delta v}{\Delta t}$$

Typical homework problem

- A motion detector measures the time delay for a click to echo and return. The computer uses the speed of sound (~ 343 m/s at room temperature) to calculate the distance to the object.

  The speed of sound changes with temperature. At 72 ºF, v_S ~ 343 m/s. At 62 ºF it is about 1% smaller.

  Suppose at 62 ºF the detector reports that an object is 2 m from the motion detector. What is its real distance from the detector?

Goal: Building Coherence

- Students enter our classes with many well-documented "misconceptions" about how the world works.
- They often learn what we teach without noticing the contradiction (context dependence).
- Standard educational "cognitive conflict" methods work but send the message that much of what they know is wrong and fails to help them learn to seek coherence.

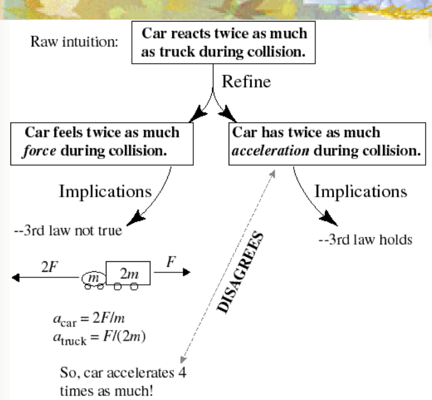
Covert message 2: Physics helps you resolve contradictions in your intuitions

- We create paired questions ("Elby pairs"),
  - one which most students are likely to answer correctly,
  - one which students are likely to answer with a common misconception.
- We then help them to see there is a contradiction in their thinking and help them resolve it.
- It sends a different covert message
  - not: Physics is right, your intuition wrong.
  - rather: Physics helps you resolve contradictions in your intuitions.

An Example: Tutorial and ILD

1. A truck rams into a parked car.
   (a) Intuitively, which is larger during the collision: the force exerted by the truck on the car, or the force exerted by the car on the truck?
   (b) Suppose the truck has mass 1000 kg and the car has mass 500 kg. During the collision, suppose the truck loses 5 m/s of speed. Keeping in mind that the car is half as heavy as the truck, how much speed does the car gain during the collision? Visualize the situation, and trust your instincts.

2. To simulate this scenario, make the "truck" (a cart with extra weight) crash into the "car" (a regular cart). The truck and car both have force sensors attached. Do whatever experiments you want, to see when Newton's 3rd law applies.



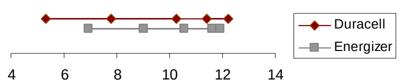
Goal: Understanding Measurement

- The traditional lab tends to focus on confirmation of theoretical results presented in lecture.
- This makes deviations from the theoretical result "experimental (or human) error" rather than being seen as providing information about the accuracy of the theoretical model or about the character of the system being observed.
- This is unnatural for biologists who tend to work with systems that have important variations over an observed population. (R. Lippmann)

Example

Which battery lasts longer, Energizer or Duracell?
A student performs an experiment measuring the number of hours two AA batteries from each brand will run a tape player.
Her data is below.

	Trial 1:	Trial 2:	Trial 3:	Trial 4:	Trial 5:	Average:
Duracell (hours)	11.4	12.2	7.8	5.3	10.3	9.4
Energizer (hours)	11.6	7.0	10.6	11.9	9.0	10.0



Descriptive Question

What happened?

"Did this battery outlast that battery?"

Predictive Question

What do my data tell me about what will happen?

"Will one brand of battery last longer?"

External Variation

Arises from weaknesses of measurement technique and equipment.

Undesirable

Can be minimized

Internal Variation

Arises from character of system.

Neutral

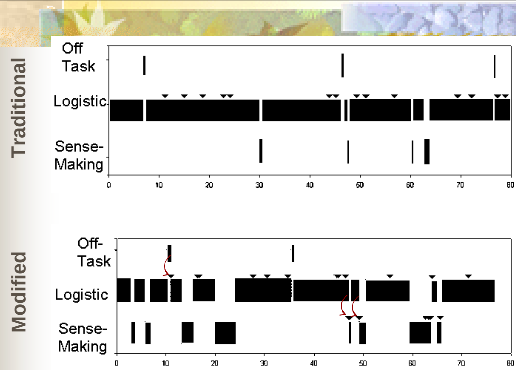
Part of investigation

Covert Message 3: Experiment is about finding out what really happens

- Sometimes experiments involve such fancy equipment that students see the experiment as *creating* the result rather than uncovering it.
- We create a new type of lab in which the students act as a mini-scientific community to explore situations and answer questions.

Modified Laboratory

- Ask questions without previously 'known' answers (both method and results)
- Use equipment or problems that will lead to significant variation.
- Require students to defend their own results and question other group's results
- Have students work to develop ideas about the importance and implications of experimental ranges by themselves.
- Let each section define their own analytical tools and terms (at first)



6. Evaluating the Results

Look at the results in 5 ways

- Mechanics concept survey pre-post
- MPEX pre-post survey
- Interviews pre-post, our students and from other classes
- Actual observed behavior in group-learning environments — tutorial and lab
- Student anonymous comments

Results

- Introducing some of these elements in Fall 2000 (N = 60)
  - We obtained the largest percentage gains we have ever recorded at Maryland on a standard mechanics conceptual test..
  - We recorded the first improvement on the MPEX that we have ever obtained in a large lecture class.
  - These results were maintained in 2001 and 2002 as additional changes were made to the course.

Evaluating Concept Learning: The Force Concept Inventory (FCI)

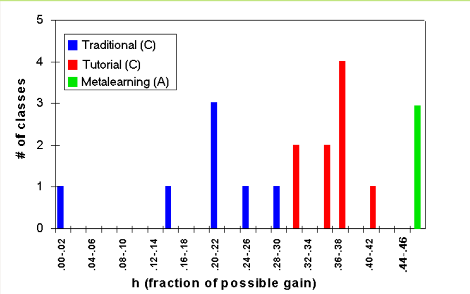
- 30 item multiple choice probe of student's understanding of basic concepts in mechanics.
- The choice of topics is based on careful thought about the fundamental issues.
- The distractors (wrong answers) are based on research that probes the students' most common responses.
- When physics faculty consider these questions, they often consider them trivial — "too easy for my students".

* *D. Hestenes, M. Wells and G. Swackhammer, The Physics Teacher* **30**:3, 141 (1992)

Imagine a head-on collision between a large truck and a small compact car. During the collision:

	With modified instruction (Physics 161) (N=280) Pre	Post
(A) the truck exerts a greater amount of force on the car than the car exerts on the truck.	62%	16%
(B) the car exerts a greater amount of force on the truck than the truck exerts on the car.	2%	1%
(C) neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck.	1%	0%
(D) the truck exerts a force on the car but the car does not exert a force on the truck.	0%	0%
(E) the truck exerts the same amount of force on the car as the car exerts on the truck. →	35%	83%

Fractional gains on conceptual test of Newtonian mechanics



The Maryland Physics Expectations (MPEX) Survey

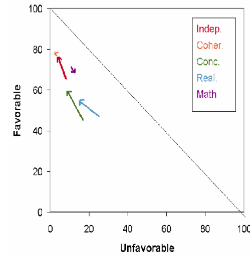
- The goal is to determine the distribution and evolution of students' cognitive attitudes —beliefs that have an effect on what they learn in a physics class.
- The MPEX contains 34 statements with which students are asked to agree or disagree on a 5 point scale.
- The MPEX has been delivered at more than 20 colleges and universities to more than 5000 students and has been translated into Chinese, Flemish, Finnish, Italian, Spanish, and Turkish.

MPEX Results

- In typical first semester calculus-based engineering classes, students give favorable results on the MPEX items about 65% of the time.
- After one semester of instruction, this typically falls to about 55%.
- These results are very robust and difficult to change with small modifications of a traditional approach (even ones that produce good conceptual gains)

MPEX Results in LtLP Class

- Coherence and math attitudes started high and remained high.
- Strong improvements in independence, coherence, and reality.
- Improvements represent both increases in favorable and decrease in unfavorable responses.



Some notable gains (N = 60; F = disagree)

- "Problem solving" in physics basically means matching problems with facts or equations and then substituting values to get a number. (#4)

	F	N	U
Pre	66%	30%	4%
Post	91%	9%	0%

- My grade in this course is primarily determined by how familiar I am with the material. Insight or creativity has little to do with it. (#13)

Pre	57%	40%	3%
Post	79%	19%	2%

- The most crucial thing in solving a physics problem is finding the right equation to use. (#19)

Pre	45%	45%	10%
Post	72%	26%	2%

Algebra-based ('00) Calc-based ('95)

		Algebra F	Algebra N	Algebra U		Calc F	Calc N	Calc U
#4	*Pre*	66%	30%	4%	*Pre*	60%	21%	19%
	Post	91%	9%	0%	*Post*	77%	13%	10%
#13	*Pre*	57%	40%	3%	*Pre*	54%	24%	22%
	Post	79%	19%	2%	*Post*	49%	23%	28%
#19	*Pre*	45%	45%	10%	*Pre*	43%	32%	25%
	Post	72%	26%	2%	*Post*	46%	26%	28%

Numerical measures are comforting, but what do students really think?

- Interviews and videos show that there are at least some students who are responding positively to this approach and shifting the ways they think about physics.

Tutorial video

Will you use any of this in two years?

According to traditional students...

No (6 / 10)
"physics has nothing to do with my major, I know I'm just going to take the class, and that's about it.... I know it's not going to help me in my later career, but biochem, at least it has some applications"

It's possible (1 / 10)
"like biomechanics, with the torque around your wrists and the pressure that you put on a bone that causes it to break.... I could see how this could be relevant if know it, but since I don't, I'm just praying that it's not going to be relevant."

They tell me I will (1 / 10)
"So I believe that people that planned the physics, they know that one day these people are going to use physics, that's why it's there. So I think it will be very helpful, because they've planned it like that."

Will you use any of this in two years?

According to our new and improved students...

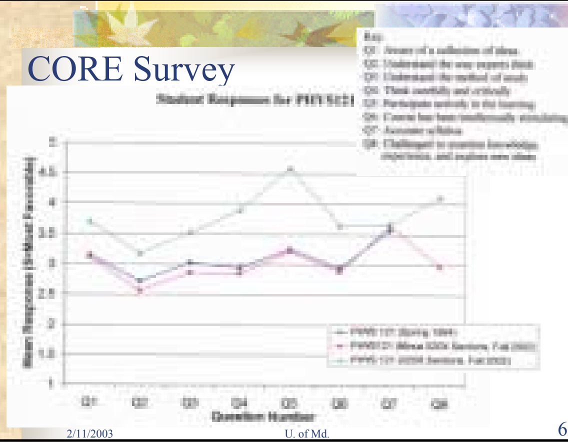
Problem Solving (7 / 13)

"I now have the ability to look back at different problems and divulge more, to kind of step back from them and overall look at it and see if there's a way I can solve it using what I know, not having to ask for help…. Because I was actually able to solve problems in other classes..."

MCAT (2 / 13)

"My friends in the other classes they sit there and memorize formulas and I would just look at something and try to understand what's behind it and I find that I do better on the [MCAT] diagnostic tests than they are, and they're just like whoa, because I used to be really bad at physics..."

CORE Survey



Students don't like it at first — it's not what they expected to have to do.

- At midsemester last term we had students give anonymous feedback: they wrote for 10 minutes describing what worked for them and what didn't.
- There were many complaints and we discussed why we were doing it in a new and different way.
- By the end of the semester, many students were enthusiastic about the method.

End of semester results

- Departmental on-line survey
  - about 120 / 160 responded
  - scores consistently above course average
  - wrote ~450 comments, mostly favorable, some wildly enthusiastic.
  - 80-90% were strongly positive (A or B)
- Not everyone liked it
  - 5-10% were strongly negative (D or E)

Sample comments

- Positive
  - I learned a lot of information in this class but more importantly learned how to truly think about my surroundings.
  - At first, I really didn't like the teaching method because it was so different from the type of thing I'm used to. Once you get into the rhythm, though, it works very well.
  - I have learned some physics, but more importantly, I have learned how to think and review my decisions.

Sample comments

- Negative
  - I did not like how he centered EVERYTHING on reasoning, Not everyone can excel at reasoning. Some people are better at the math aspect of physics.
  - It got really annoying that so many problems involved more of making up numbers than actually using formulas.

7. Conclusions

The method seems to work but…

- The approach produces much stronger conceptual and attitudinal gains than traditional.
- Modifying student expectations about what is going to happen in the class is difficult.
- 121 students are capable of significantly more "thinking" than we traditionally ask of them.
- Can it be done with standard TA's and faculty?
- Can elements be integrated into the Department's standard repertoire?