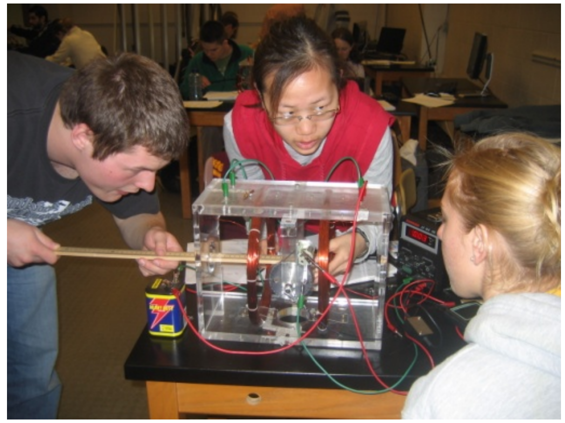
The Role of Problem Solving in Introductory Physics – Why, What, and How?



Ken Heller

School of Physics and Astronomy

University of Minnesota

25 year continuing project to improve undergraduate education with contributions by:
Many faculty and graduate students of U of M Physics Department
In collaboration with U of M Physics Education Research (PER) Group

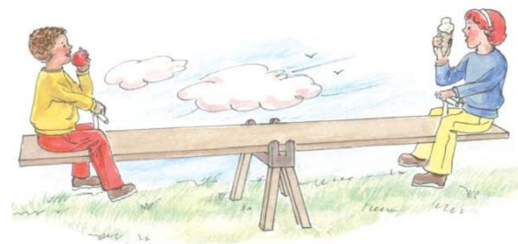
Current PER group: Bijaya Aryal, Evan Frodermann, Ken Heller, Leon Hsu, Christy Krouse, Jia-Ling Lin, Eugene Park, Steve Pliam, Qing Xu, Jie Yang

Details at http://groups.physics.umn.edu/physed/

Supported in part by Department of Education (FIPSE), NSF, and the University of Minnesota

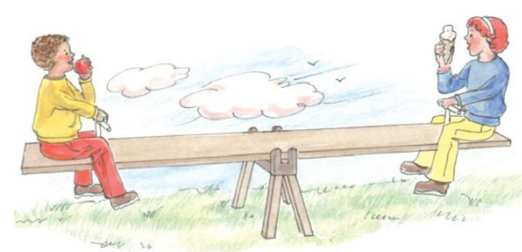
Problem Solving in Introductory Physics
A Guide for Discussion

1. **Designing Improvement**
2. **Why Problem Solving?**
3. **System Components**



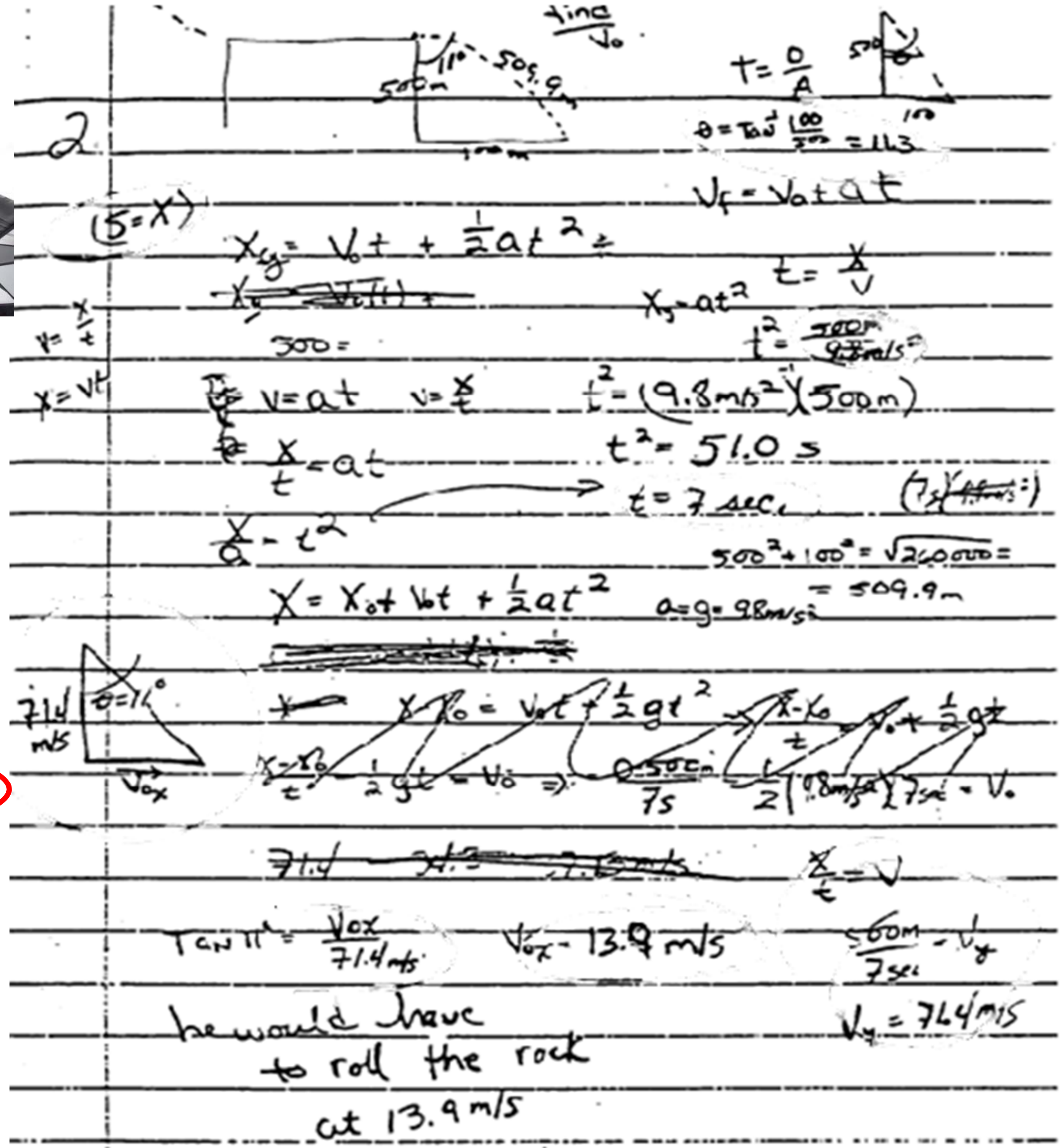
- Course (content & structure)
- Students (characteristics & difficulties)
- Instructors (beliefs & values)
- Customers (expectations & desires)

4. **Some Data**



callcentertoday.com

What Students Show Us After Instruction



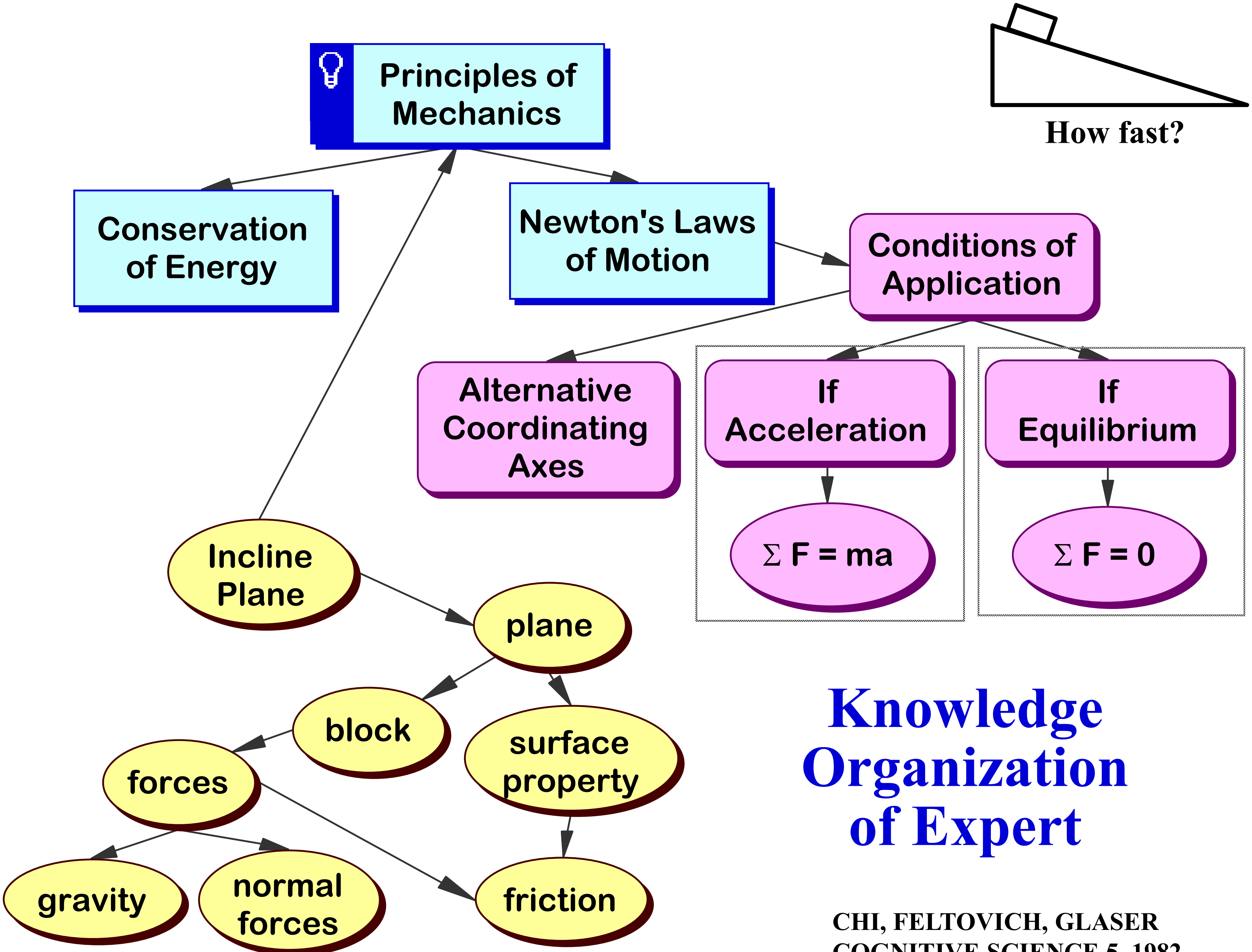
We are not happy.
Neither are our students.

Solution

- Get better students
- Get better teachers
- Do things differently

Students do not think the same way we do

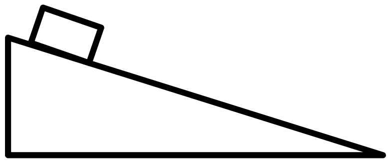
We are experts
They are novices

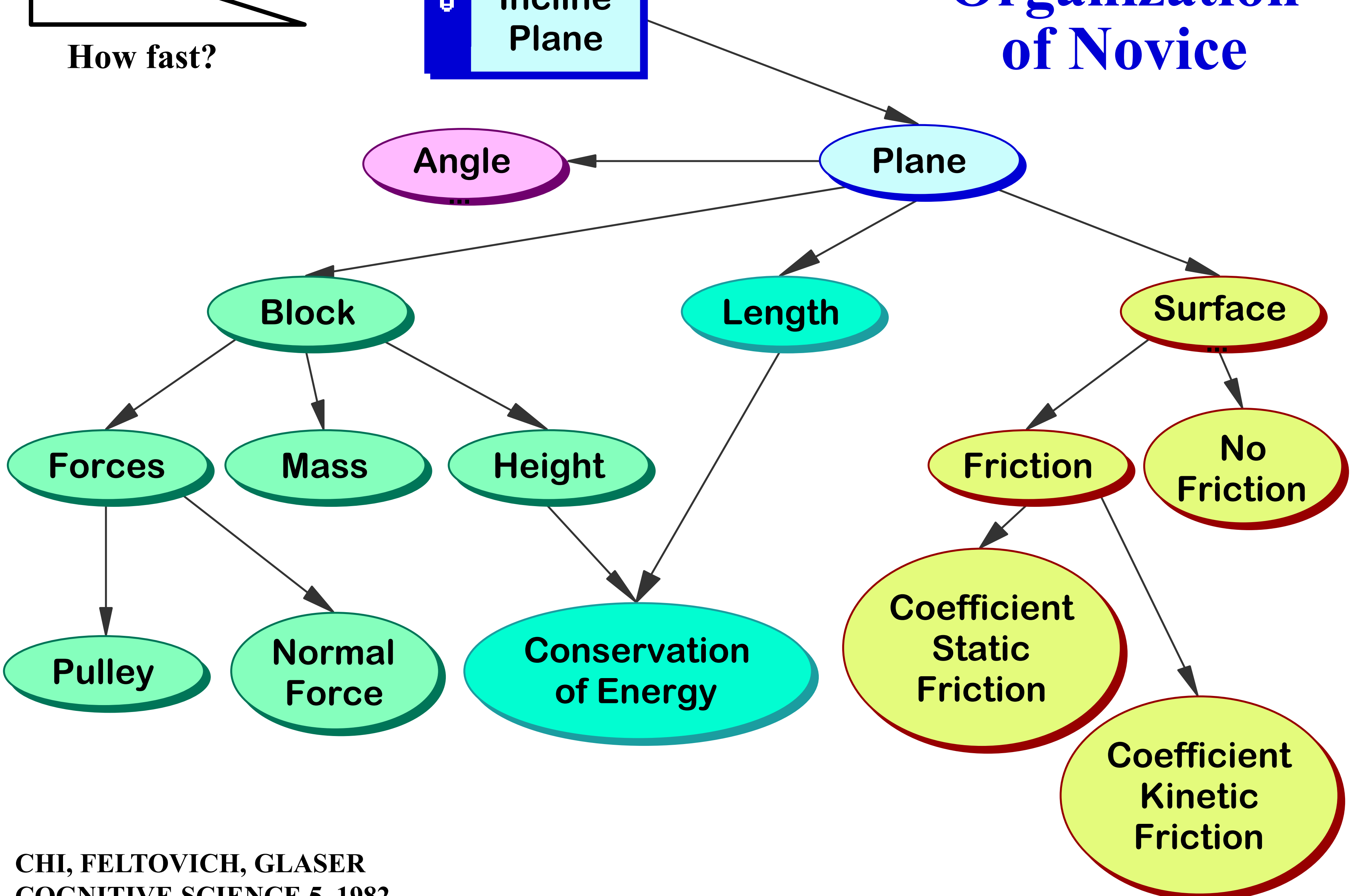


Knowledge Organization of Expert

CHI, FELTOVICH, GLASER
COGNITIVE SCIENCE 5, 1982

Knowledge Organization of Novice





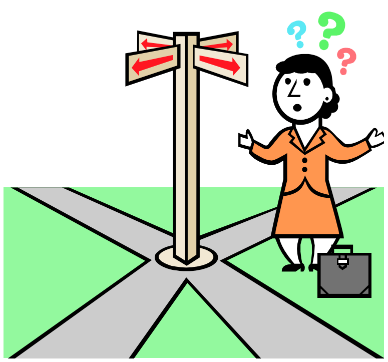
CHI, FELTOVICH, GLASER
COGNITIVE SCIENCE 5, 1982

To Succeed You Need a Goal

University of Minnesota Women's Hockey Team NCAA Champions 2012 & 2013

There are several possible goals of an introductory physics course.

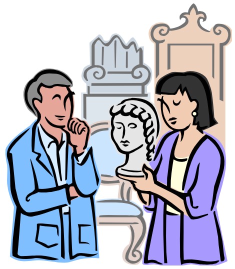
You cannot accomplish them all



- **Qualitative ↔ Quantitative**
- **Concepts ↔ Problem Solving**
- **Breath ↔ Depth**
- **Applied ↔ General**
- **Topic 1 ↔ Topic 2**

Decisions are necessary

Define the Goals



Who are the customers?

- The country.
- Faculty who require their students to take the class.
- The discipline of physics.
- The physics department.
- Students who take the class.

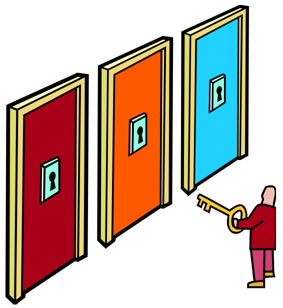
Design a questionnaire for faculty in other departments

Overall Goals
- Free response
- List with rating scale (1 to 5)

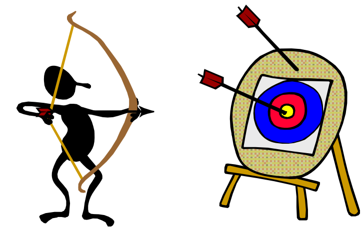
Content
- Forced selection of chapters from a standard text.

Type of Labs
- Free response
- List with rating scale

Type of Discussion Section
- Free response
- List with rating scale



Faculty Goals



Many different goals could be addressed through this course. Would you please rate each of the following possible goals in relation to its importance for your students on a scale of 1 to 5?

Algebra-based Course (24 different majors) 1987

4.7 Basic principles behind all physics

4.2 General qualitative problem solving skills

4.2 Overcome misconceptions about physical world

4.0 General quantitative problem solving skills

4.0 Apply physics topics covered to new situations

Problem Solving is Important

What Do Other Faculty Want? (5 pt scale)

Goals: Calculus-based Course (88% engineering majors) 1993

- 4.5 Basic principles behind all physics
- 4.5 General qualitative problem solving skills
- 4.4 General quantitative problem solving skills
- 4.2 Apply physics topics covered to new situations
- 4.2 Use with confidence

Goals: Algebra-based Course (24 different majors) 1987

- 4.7 Basic principles behind all physics
- 4.2 General qualitative problem solving skills
- 4.2 Overcome misconceptions about physical world
- 4.0 General quantitative problem solving skills
- 4.0 Apply physics topics covered to new situations

Goals: Biology Majors Course 2003

- 4.9 Basic principles behind all physics
- 4.4 General qualitative problem solving skills
- 4.3 Use biological examples of physical principles
- 4.2 Overcome misconceptions about physical world
- 4.1 General quantitative problem solving skills
- 4.0 Apply physics topics covered to real world situations
- 4.0 Know range of applicability of physics principles

Topics - Physics for Biology Majors

%T		%*	
90	✓	15	Potential energy and conservation of energy
85	✓	15	Kinetic energy and work
85	✓	20	Entropy and the second law of thermodynamics
85	✓	15	Electric charge and force
85	✓	13	Electric potential
80	✓	0	Linear motion
80	✓	0	Forces and Newton's Laws
75	✓	15	Units, dimensions and vectors
75	✓	5	Temperature and ideal gas
75	✓	0	Electric field
75		5	Molecules and gases (e.g. probability distributions of velocity)
75	✓	9	Mirrors and lenses
70		0	Momentum and collisions
70	✓	9	Nuclear physics and radioactive decay
65	✓	0	Two dimensional motion
65		0	Gravitation
65		4	Currents in materials (e.g. resistance, insulator, semiconductors)
65	✓	15	Heat flow and the first law of thermodynamics
65	✓	0	Magnetic forces and fields
60	✓	4	Geometrical optics (e.g. reflection and refraction)
60	✓	0	Diffraction
55	✓	0	Oscillatory motion
55	✓	4	Currents and DC circuits

Making Hard Choices

19/23 Chapters

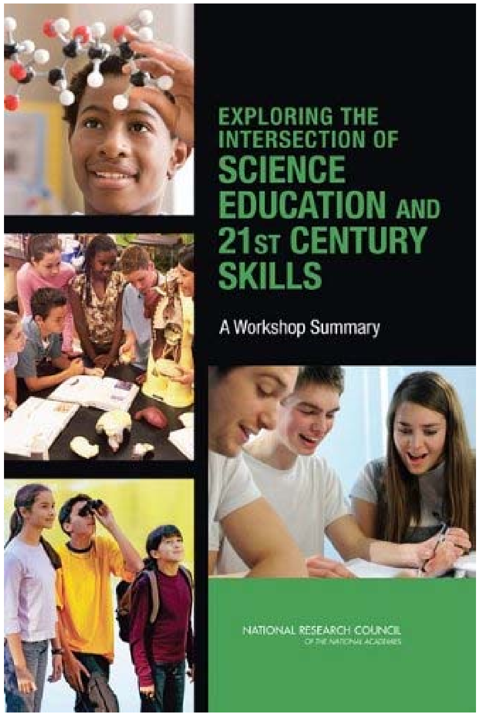
Topics - Physics for Biology Majors

%T		%*	
50	✓	0	~~Rotations and~~ torque
45	✓	5	Applications of Newton's laws
45		0	Angular momentum
45		0	Gauss' law
45	✓	4	Currents and magnetic fields (e.g. Ampere's law, ~~Biot-Savart law)~~
45	✓	0	Interference
40	✓	5	Fluid mechanics
40		5	Properties of solids (e.g. stress, strain, thermal expansion)
40	✓	0	Capacitors ~~and dielectrics~~
40		4	Maxwell's equations and electromagnetic waves
40		0	Relativity
35	✓	4	Faraday's law
35	✓	0	Superposition and interference of waves
30		0	Mechanical waves
30	✓	0	Statics
30		0	Magnetism and matter (e.g. ferromagnetism, diamagnetism)
30		9	AC circuits
30		0	Atomic physics
20		0	Quantum physics
15		0	Magnetic Inductance
15		0	Particle physics
0		0	Other. Please specify.

9/21 Chapters

2 semesters (28 wks) = 28 Chapters

The Country Needs An Educated Workforce



NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES (2010)

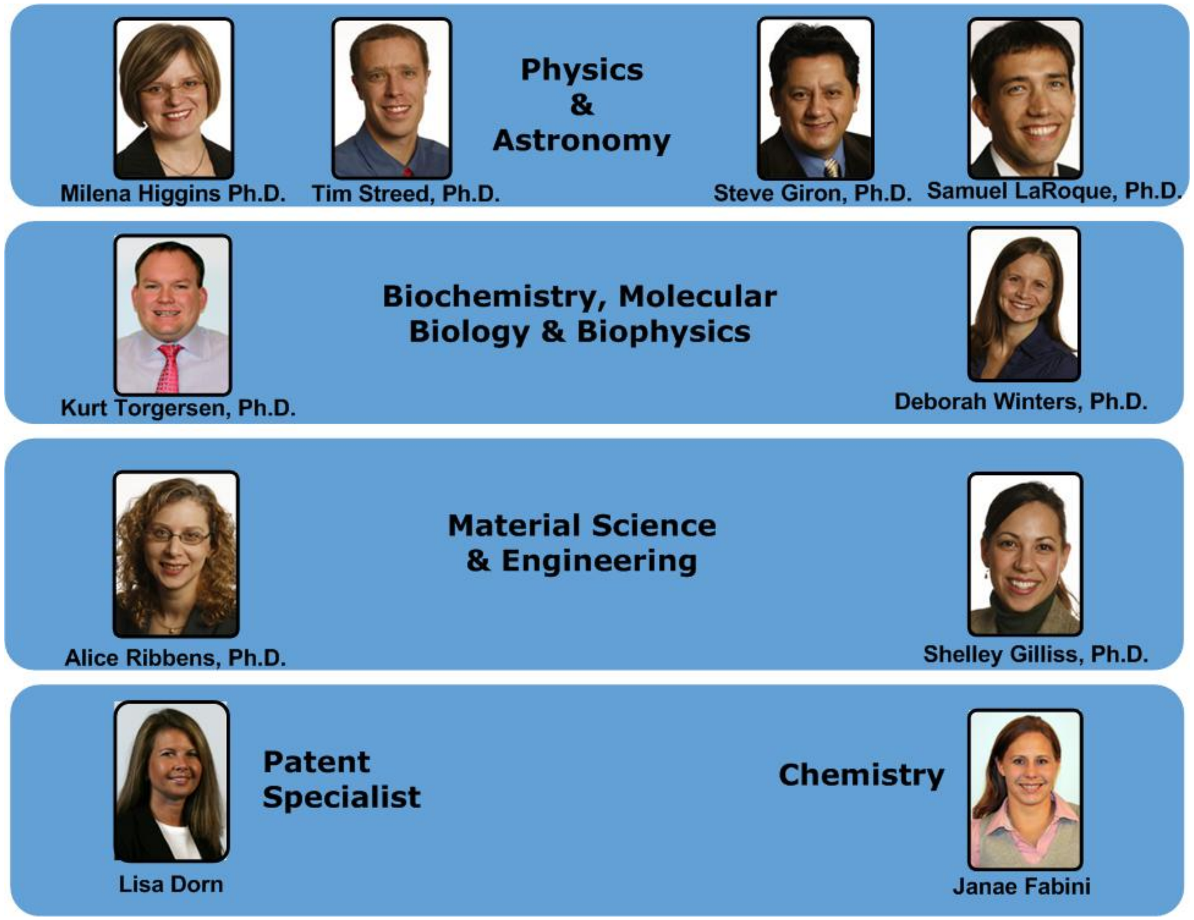
21st Century Skills

- Adaptability:
- Complex communication/social skills:
- Self-management/self-development:
- Systems thinking:
- Non-routine problem solving:
- Diagnose the problem.
- Link information.
- Reflect on solution strategy.
- Switch strategy if necessary.
- Generate new solutions.
- Integrate seemingly unrelated information.

Problem Solving Is Not Just For Science & Engineering

Science department of a large national law firm

ROBINS, KAPLAN, MILLER & CIRESI L.L.P.



Physics Department Open House 11/11/10

What's a Physicist Doing in a Law Firm?

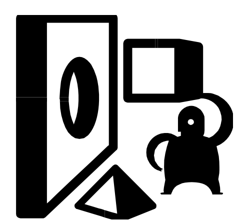
Milena Higgins

Chief Scientist

U of Mn PhD 1996 Biophysics

Q: How has Physics Helped You?

A: "It's all problem solving!"



University of Minnesota Strategic Planning - 2007

At the time of receiving a bachelor's degree, students will demonstrate the following qualities:

University of Minnesota

1. the ability to identify, define, and solve problems
2. the ability to locate and evaluate information
3. mastery of a body of knowledge and mode of inquiry
4. an understanding of diverse philosophies and cultures in a global society
5. the ability to communicate effectively
6. an understanding of the role of creativity, innovation, discovery, and expression in the arts and humanities and in the natural and social sciences
7. skills for effective citizenship and life-long learning.

The syllabus for every course must say which of these 7 it addresses

Intro Physics Contributes to 1, 2, 3, 5, 7

What is a Problem?

A problem is a situation that you do not know how to resolve.

If you know how to do it, it is not a problem.

Solving a problem requires making decisions that connect what you know in new ways.

M. Martinez, Phi Delta Kappan, April, 1998

Solving Physics Problems

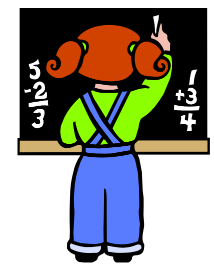
Expert: Solving a problem requires constructing a set of decisions that logically connect the situation to the goal using basic principles.

In Physics these decisions are typically about

- Visualizing a situation
- Specifying goals
- Making assumptions
- Identifying useful ideas
- Learning new ideas
- Connecting ideas using techniques such as diagrams, logic, mathematics
- Evaluating the process and its results

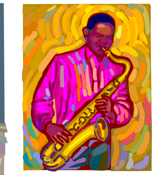
Novice: Solving a problem requires a following a recipe that connects the situation to the goal.

Novice Problem-solving Framework



STEP 1	**What Kind of Problem is This?**	**Which pattern does it match?**
STEP 2	**What Equations Are Needed?**	**One should match this situation**
STEP 3	**Do Some Math**	**Plug in numbers**
STEP 4	**Do Some More Math**	**Manipulate equations to get an answer.**
STEP 5	**Is It Done?**	**Did I get an answer?**

Problem-solving Framework
Used by experts in all fields



G. Polya, 1945

Chi, M., Glaser, R., & Rees, E. (1982)

STEP 1 Recognize the Problem

What's going on and what do I want?

Not a linear sequence.
Requires continuous reflection and iteration.

STEP 2 Describe the problem in terms of the field

What does this have to do with ...... ?

STEP 3 Plan a solution

How do I get what I want?

STEP 4 Execute the plan

Let's get the answer.

STEP 5 Evaluate the solution

Can this be true?

"I was a student in first year physics you taught 20 years ago. Since those days I have made a good living as an RF integrated circuit design engineer. I am writing to let you know not a week goes by without a slew of technical problems to be solved, and the first thing that comes to mind is the "define the problem" which I recently reminded myself that it was you who instilled this ever so important step in problem solving. I would like to thank you because your influence has helped me excel and become a better engineer."

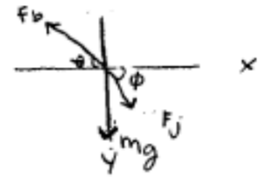
email received June 22, 2012

Problem Solving After Instruction

Trying to solve a problem by making logically connected decisions.

Knowns
$\theta = 80°$
$V_m = 3.76\ L = 3760\ mL$

Force Diagram



Target: F_j = Force of joint

Approach: Use Forces
$\Sigma F_x = 0$
$\Sigma F_y = 0$
Use Torque
$\Sigma \tau = 0$

$\rho = \frac{m}{V}$

$\rho V_m = m$

assume density of milk is similar to water. $= 1\ g/cm^3 = 1\ g/mL = .001\ kg/mL$

$\Sigma F_x = 0$
$F_{jx} - F_{bx} = 0$

$\Sigma F_y = 0$

$F_{by} - mg - F_{jy} = 0$

$\Sigma \tau = 0$ (joint is pivot point)

$F_{by}(1/6\,L) - mgL = 0$

$F_b \cos\theta = F_{bx}$
$F_b \sin\theta = F_{by}$
$F_{jy} = F_j \sin\phi$
$F_{jx} = F_j \cos\phi$
$F_j^2 = F_{jx}^2 + F_{jy}^2$

equation		unknown
$F_j^2 = F_{jx}^2 + F_{jy}^2$	1	F_{jx}, F_{jy} 2
$F_{by} - mg - F_{jy} = 0$	2	F_{by} 3
$F_{jx} - F_{bx} = 0$	3	F_{bx} 4
$F_{by}(1/6\,L) - mgL = 0$	4	
$F_{bx} = F_b \cos\theta$	5	F_b 5
$F_{by} = F_b \sin\theta$	6	

$F_b = \frac{F_{by}}{\sin\theta}$

$\frac{F_{by}}{\sin\theta} \cos\theta = F_{bx}$

$6mg = F_{by}$

$F_{jx} = \frac{6mg}{\sin\theta} \cos\theta$

$F_{jy} = F_{by} - mg = 6mg - mg$

$F_j = \sqrt{\left(\frac{6mg}{\sin\theta}\cos\theta\right)^2 + (6mg - mg)^2}$

Plug in ϕ — ρV for m

$F_j = \sqrt{\left(\frac{6\rho V g}{\sin\theta}\cos\theta\right)^2 + (5\rho V g)^2}$

$= \sqrt{\left(\frac{6(.001)\,3760g}{\sin 80}\cos 80\right)^2 + (5(.001)(3760g))^2} =$

43.3 N

units $\left(\frac{kg}{mL} \cdot mL\,\frac{m}{s^2}\right)^2 + \left(\frac{kg}{mL} \cdot m \cdot \frac{m}{s^2}\right)^2 = \sqrt{\frac{kg^2 m^2}{s^4}} = kg\,m/s^2 = N$ ✓

43.3 N is the amount needed to lift an ≈ 4.3 kg object straight off the ground this is reasonable

Characterizing & Quantifying Expert-like Problem Solving

Almost Independent Dimensions

- **Useful Description**
  - organize information from the problem statement symbolically, visually, and/or in writing.
- **Physics Approach**
  - select appropriate physics concepts and principles
- **Specific Application of Physics**
  - apply physics approach to the specific conditions in problem
- **Mathematical Procedures**
  - follow appropriate & correct math rules/procedures
- **Logical Progression**
  - overall the solution progresses logically; it is coherent, focused toward a goal, and consistent (not necessarily linear)

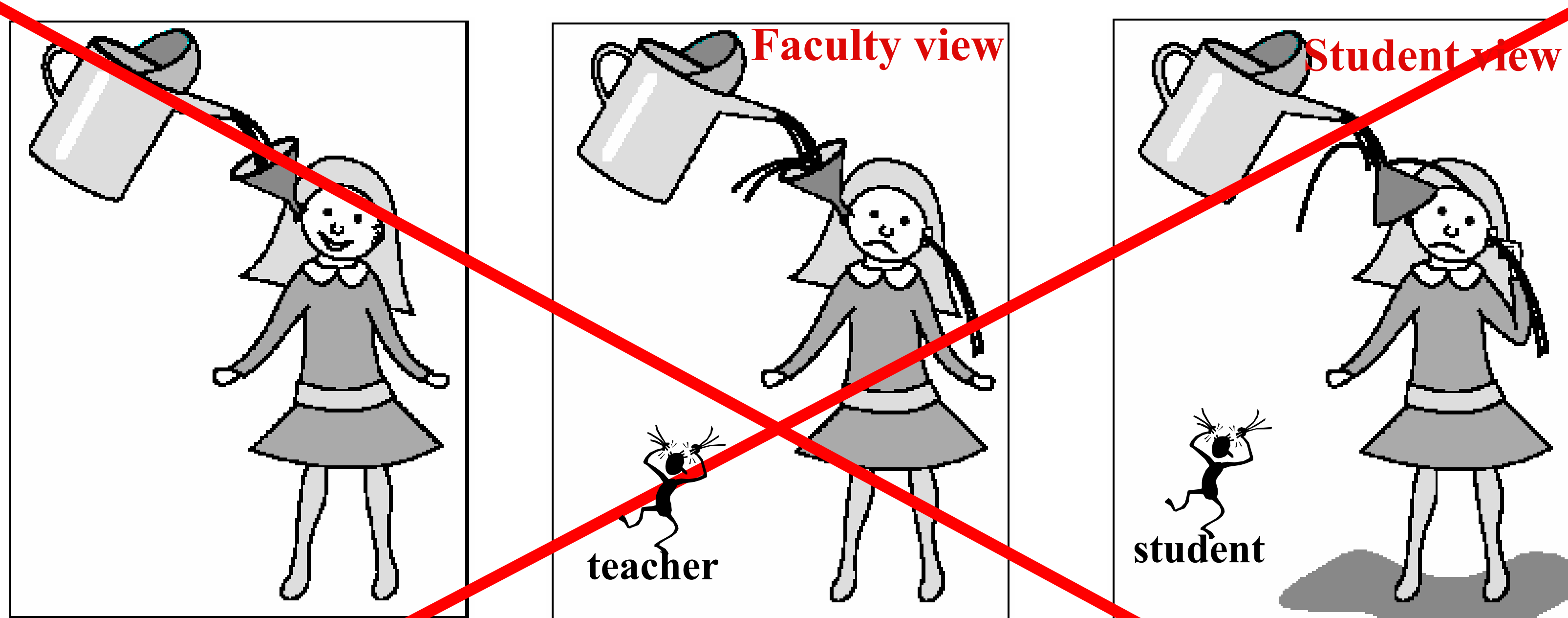
J. Docktor (2009) based on previous work by:

J. Blue (1997); T. Foster (2000); T. Thaden-Koch (2005);

P. Heller, R. Keith, S. Anderson (1992)

The Teaching Process
The Clear Explanation Misconception

Common Source of Frustration of Faculty, TAs, Students, & Administrators



Instructor imparts knowledge to students by explaining things clearly.

Little knowledge is retained.

Student's Fault

Impedance mismatch between student and instructor.

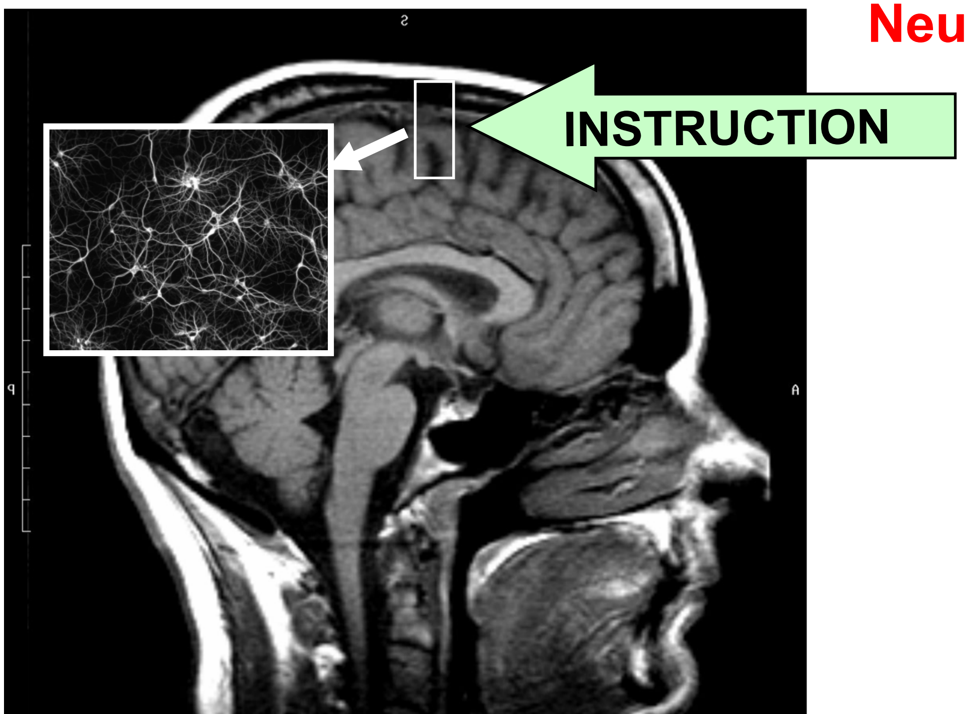
Instructor's Fault

Learning is much more complicated

Leonard et. al. (1999). Concept-Based Problem Solving.

Learning is a Biological Process

Neural Science Gives Constraints



Neurons that fire together, wire together

Simplification of Hebbian theory:
Hebb, D (1949). *The organization of behavior*. New York: Wiley.

Brain MRI from Yale Medical School

Neuron image from Ecole Polytechnique Lausanne

Knowing is an individual's neural interconnections

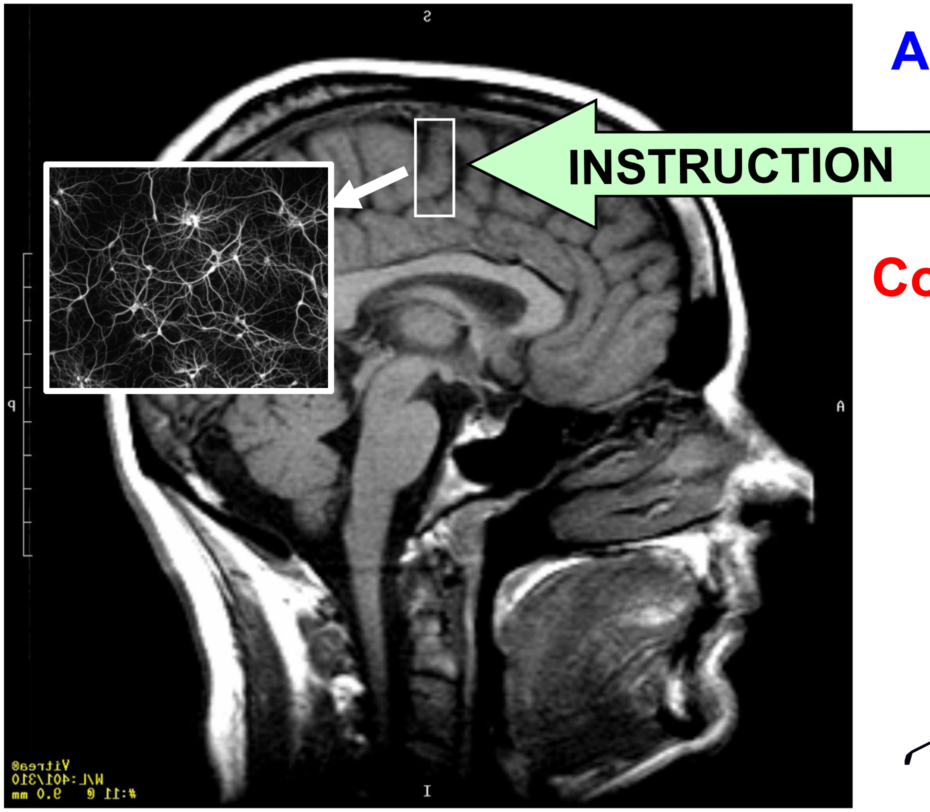
Operationally, a student knows something if they can use it in novel (for them) situations and communicate that usage.

Learning is expanding and changing the network of neural connections

Teaching is putting the student in a situation that stimulates their neural activity to renovate the relevant network of neural connections.

Teaching requires forcing a student's Mental Engagement

Learning is Too Complex to Predetermine



Apprenticeship Works

Cognitive Apprenticeship

Learning in the environment of expert practice

- Why it is important?
- How it is used?
- How is it related to what I already know?

model

coach

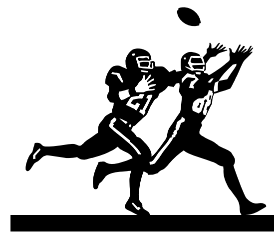
fade

Collins, Brown, & Newman (1990)

Brain MRI from Yale Medical School
Neuron image from Ecole Polytechnique Lausanne

Learning to Solve Problems Requires Practice

BUT



“Practice does not make perfect.
Only perfect practice makes perfect.”

Vince Lombardi (expert on coaching)

This is not perfect practice

A block of mass m = 2.5 kg starts from rest and slides down a frictionless ramp that makes an angle of θ= 25^{o} with respect to the horizontal floor. The block slides a distance *d* down the ramp to reach the bottom. At the bottom of the ramp, the speed of the block is measured to be *v* = 12 m/s.

(a) Draw a diagram, labeling θ and d.

(b) What is the acceleration of the block, in terms of g?

(c) What is the distance *d*, in meters?

Robs students of practice making easy decisions
Does not reinforce motivation – reason to solve problems
Students do not practice linking to their existing information

Original

A block of mass m = 2.5 kg starts from rest and slides down a frictionless ramp that makes an angle of θ= 25° with respect to the horizontal floor. The block slides a distance *d* down the ramp to reach the bottom. At the bottom of the ramp, the speed of the block is measured to be *v* = 12 m/s.

(a) Draw a diagram, labeling θ and d.

(b) What is the acceleration of the block, in terms of g?

(c) What is the distance *d*, in meters?

Better

A 2.5 kg block starts from the top and slides down a slippery ramp reaching 12 m/s at the bottom. How long is the ramp? The ramp is at 25° to the horizontal floor .

Practice making decisions

Practice making assumptions

Even Better

You are working with a design team to build a simple system to transport boxes from one part of a warehouse to another. In the design, boxes are placed at the top of the ramp so that they slide to their destination. A box slides easily because the ramp is covered with rollers. Your job is to calculate the maximum length of the ramp if the heaviest box is 25 kg and the ramp is at 5.0° to the horizontal. To be safe, no box should go faster than 3.0 m/s when it reaches the end of the ramp.

Context Rich Problem

Requires student decisions.

Practice making assumptions.

Connects to student reality.

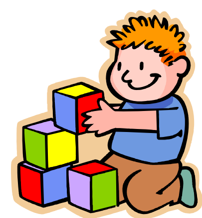
Has a motivation (why should I care?).

The Dilemma

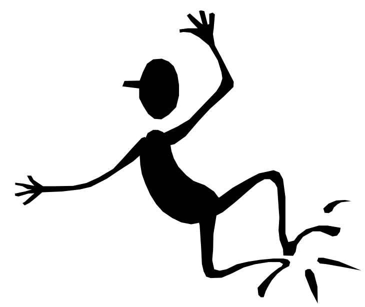
Start with complex problems so novice problem solving framework fails

Difficulty using an expert-like problem solving framework with challenging problems.

Why change?



Start with simple problems to learn expert-like problem solving framework.



Success using novice framework.

Why change?

Coaching is the necessary ingredient that allows students to use complex problems that require practicing an expert-like framework.

Cooperative Groups

Provide peer coaching and facilitates expert coaching

Allow success solving complex problems by practicing an expert-like problem solving framework from the beginning of the course.

- **Positive Interdependence**
- **Face-to-Face Interaction**
- **Individual Accountability**
- **Explicit Collaborative Skills**
- **Group Functioning Assessment**

Johnson & Johnson, 1978

Email 8/24/05

"Another good reason for cooperative group methods: this is how we solve all kinds of problems in the real world - the real academic world and the real business world. I wish they'd had this when I was in school. Keep up the great work."

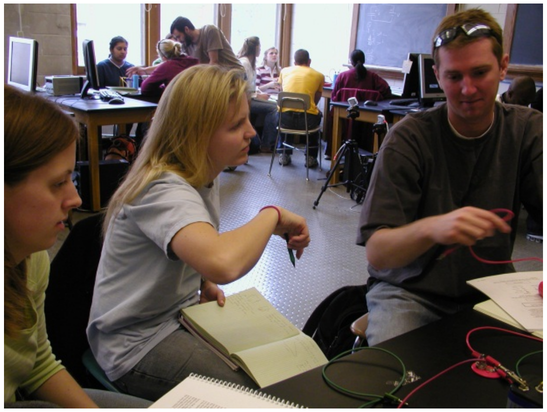
Vice President,
Handhelds Hewlett Packard

Cooperative Group Problem Solving is an Implementation of Cognitive Apprenticeship

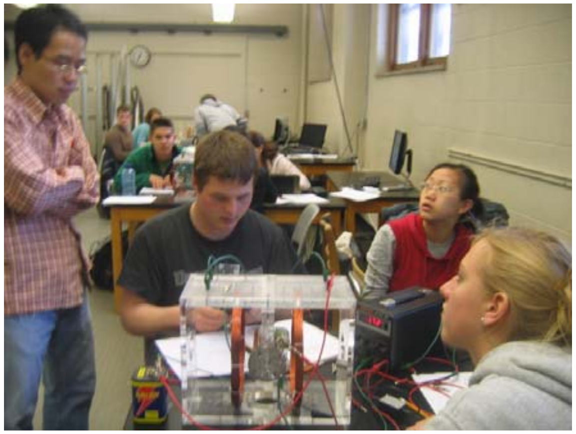
There is no benefit in just having students work in groups.

Essential Elements

1. Demonstrate an Organized Framework for Problem Solving
2. Problems that Require Using an Organized Framework
3. Cooperative Groups to provide coaching to students while solving problems
4. Tests that Require Students to Solve Complex Problems Using an Organized Framework.
5. Appropriate Grading

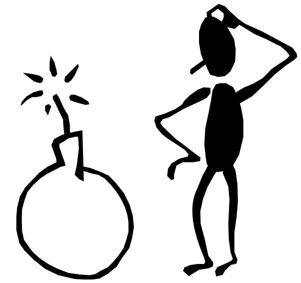


Peer coaching



Instructor coaching

Identify Critical Failure Points



1. Inappropriate Tasks

- Problems that have no obvious decisions.
- Problems that do not connect to student experience.
- Problems that one person can easily solve.

2. Inappropriate Grading

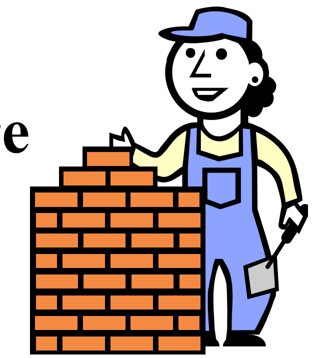
- Grading on the curve (penalize those who help others)
- No reward for both individual and group learning.
- Only the answer, not process, is rewarded.

3. Poor Structure and Management of Groups

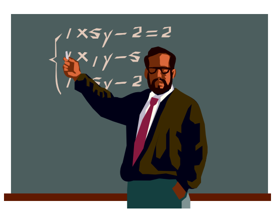
- Students not required to search their own knowledge (use books & notes allowed)
- Students do not co-construct a solution, they work independently and compare results.

Building A Course Using Cognitive Apprenticeship

- Demonstrate an Expert-like Problem Solving Framework
  - Emphasize making decisions using fundamental physics
  - Writing as working memory
  - Rule-based mathematics



- Practice & Test Using Problems that Require
  - An organized framework
  - Physics conceptual knowledge
  - Connection to existing knowledge
- Use Existing Course Structure
  - Lectures and web material MODELING
  - Discussion Sections COACHING
  - Labs COACHING
- Scaffolding to Support Problem Solving



Modeling

Peer

Instructor

Coaching

Fading

Course Structure @ Minnesota

LECTURES	**Three hours** each week, sometimes with informal cooperative groups, **peer coaching**. **Model** constructing knowledge, **model** using the problem solving framework.
DISCUSSION SECTION	**One hour** each Thursday -- groups practice using problem-solving framework to solve context-rich problems. **Peer coaching, TA coaching.**
LABORATORY	**Two hours** each week -- ***same*** groups practice using framework to solve concrete experimental problems. ***Same*** TA. **Peer coaching, TA coaching.**
TESTS	Friday -- problem-solving quiz & conceptual questions (usually multiple choice) every three weeks. **Fading**

Scaffolding – computer reading tests, clickers, JITT, limit formula usage, sample quizzes, problem solving manual, context rich problems

Cooperative Group Problem Solving Propagates Slowly Through the Department

Introductory Physics

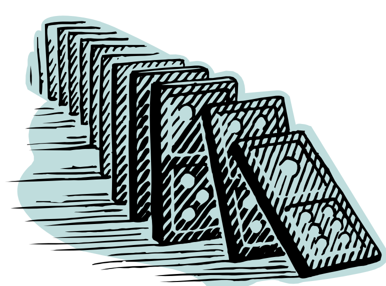
Algebra-based Course for Pre Professionals (24 different majors) 1987

Calculus-based Course for Engineering and Physical Science Students (88% engineering majors) 1993

Calculus based Course for Biology Majors (1/3 premeds) 2003

Upper Division Physics Major Courses 2002

Analytic Mechanics
Electricity & Magnetism
Quantum Mechanics

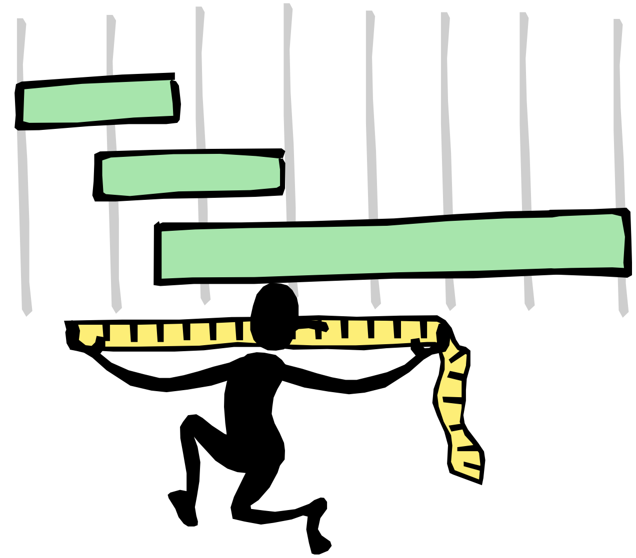


Graduate Courses 2007

Quantum Mechanics

Budget constraints have prevented additional requested expansion into other courses

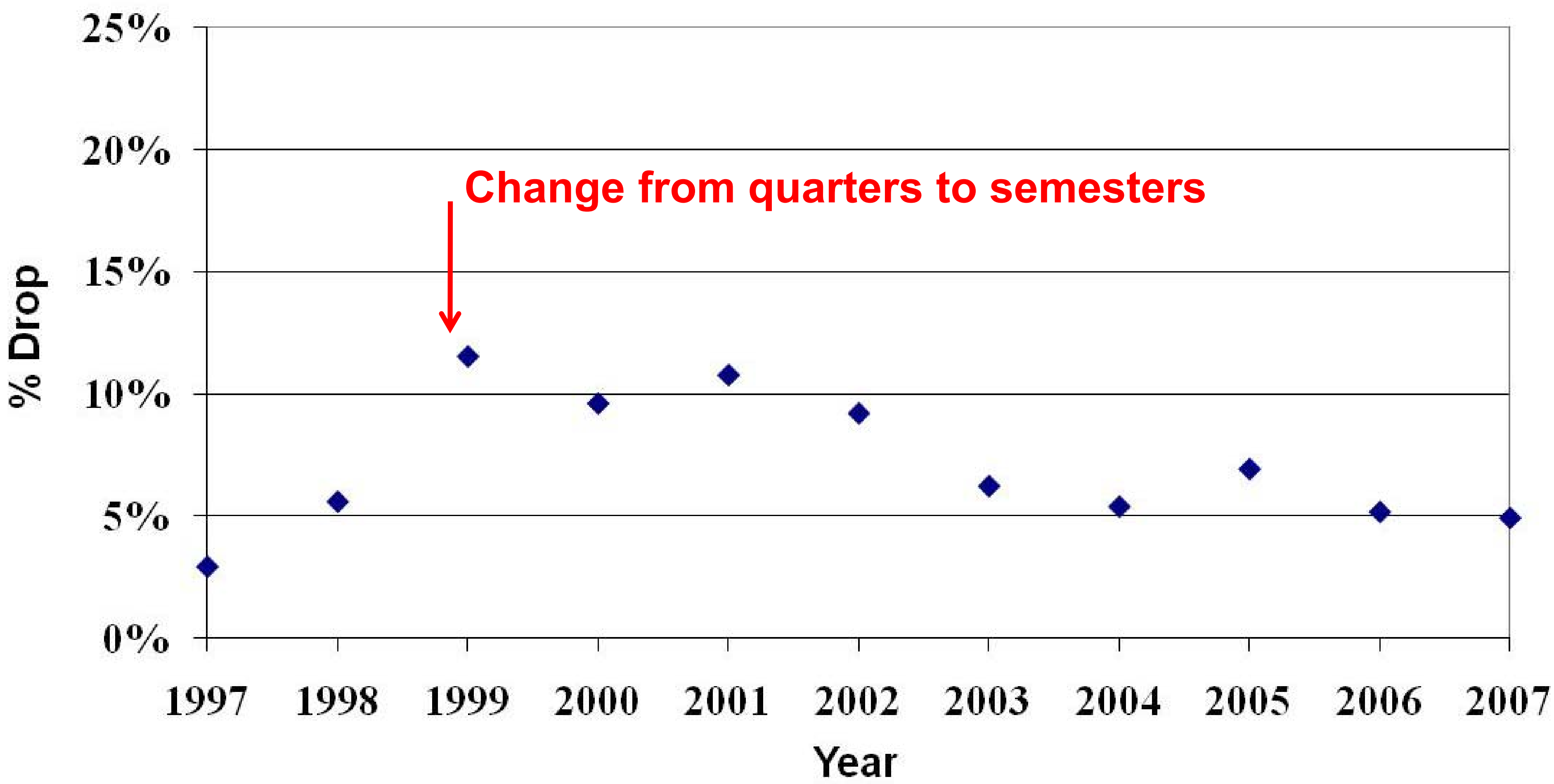
Assessment



- Problem Solving Skill
- Drop out rate
- Failure rate
- National concept tests (FCI, BEMA)
- National attitude survey (CLASS)
- Math skills test
- What students value in the course
- Engineering student longitudinal study
- Faculty use
- Adoption by other institutions and other disciplines

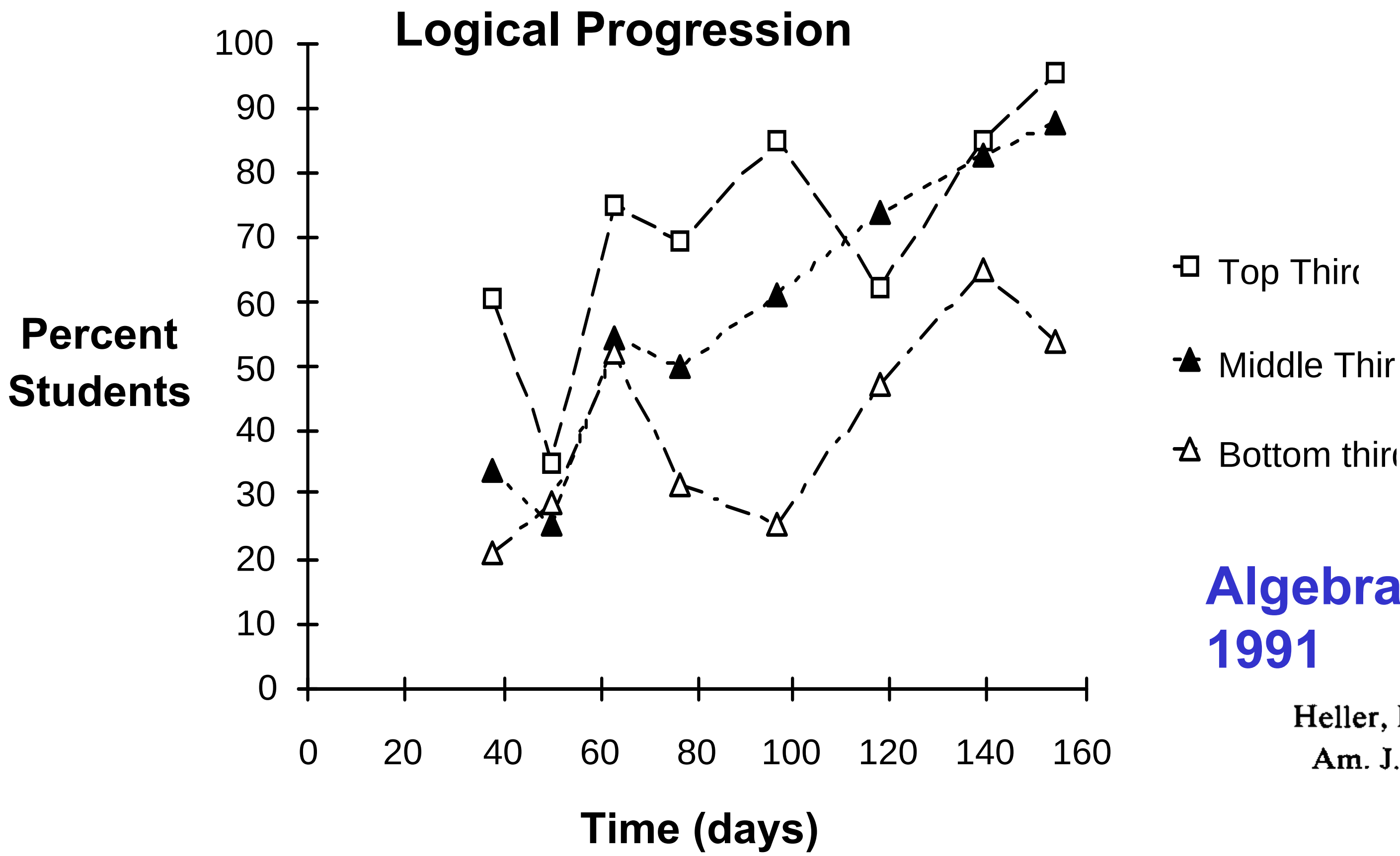
Retention after Implementation – Physics

Previous dropout + F/D rate was ~ 30%



Dropout rate ~ 6%, F/D rate ~ 3% in all classes

Improvement in Problem Solving



Algebra based physics 1991

Heller, Keith, and Anderson
Am. J. Phys., Vol. 60, No. 7, July 1992

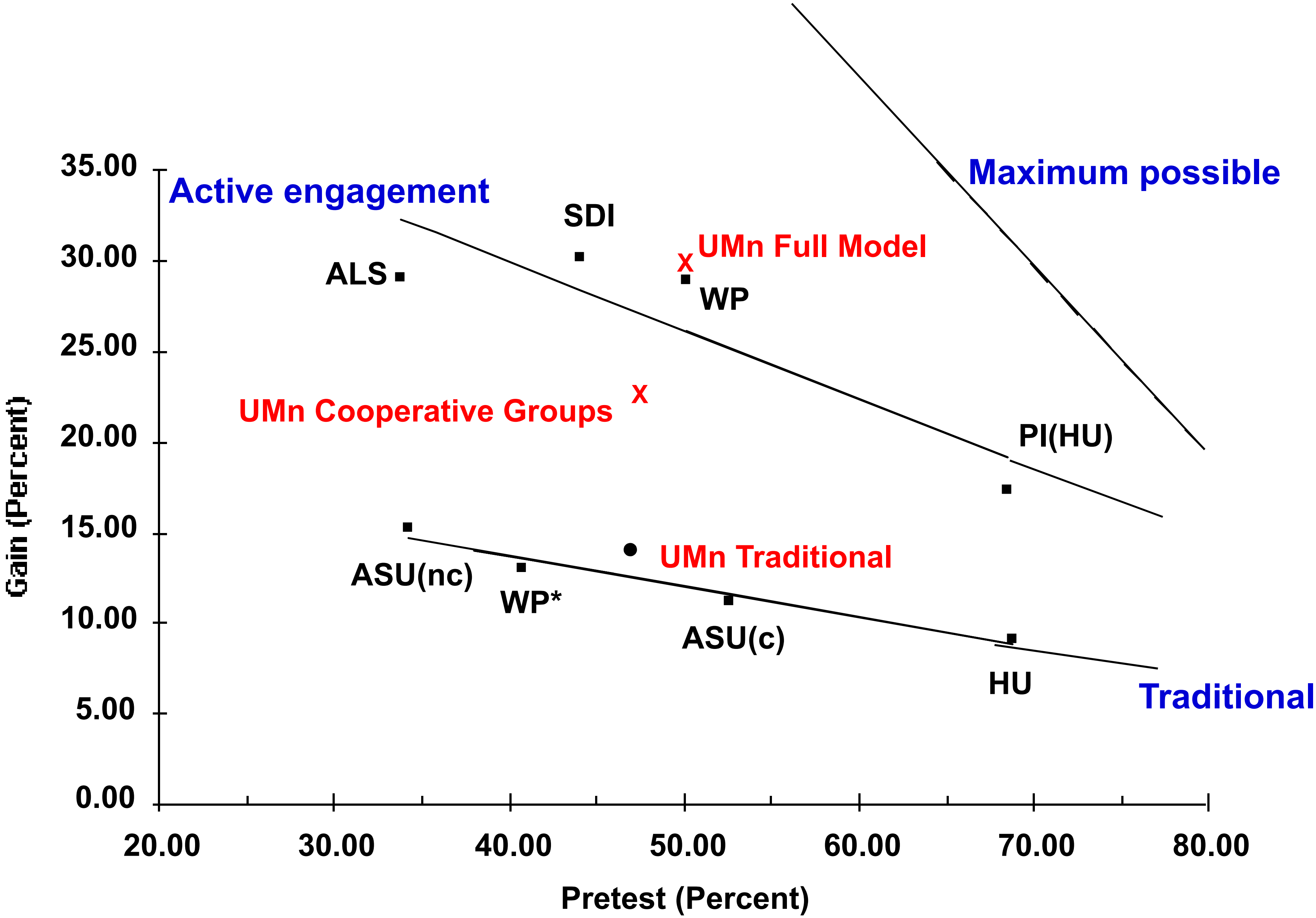
General Approach - does the student understand the physics

Specific Application of the Physics - starting from the physics they used, how did the student apply this knowledge?

Logical Progression - is the solution logically presented?

Appropriate Mathematics - is the math correct and useful?

Gain on Force Concept Inventory (Hake plot)



Hake, Am. J. Phys. 66 (1), January 1998

The End

Please visit our website for more information:

http://groups.physics.umn.edu/physed/

The best is the enemy of the good.

"le mieux est l'ennemi du bien"

Voltaire