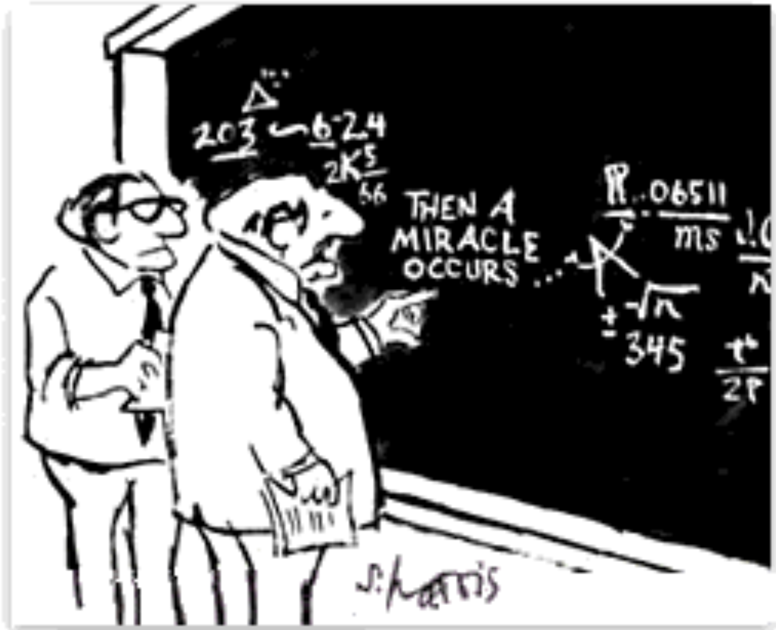
“I Understand the Physics, But I Can’t Solve the Problems” – Can Computers Help?



“I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO.”

Ken Heller
Physics and Astronomy
University of Minnesota

27 year continuing project to improve undergraduate problem solving by:
Many faculty and graduate students of U of M Physics Department
In collaboration with U of M Physics Education Group

Current PER group: Bijaya Aryal, Evan Frodermann, Ken Heller, Leon Hsu, Eugene Park, Emily Smith, Jie Yang + undergrads + visitors

For more information google: PER minnesota

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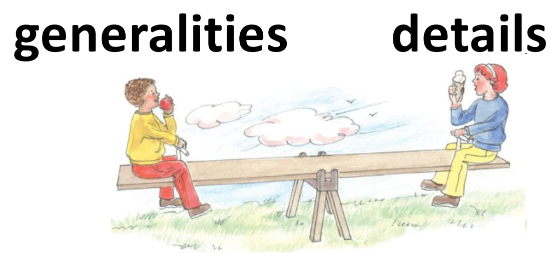
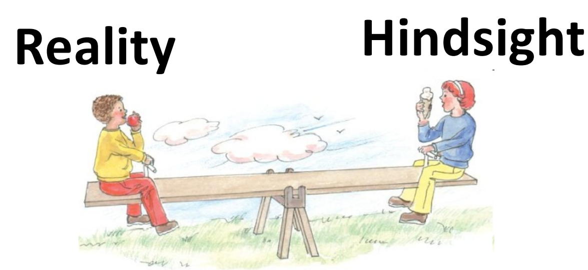
A Guide for Discussion

- ➢ Why Teach Problem Solving?
- ➢ What Is Meant by Problem Solving?
- ➢ Context from learning theory
- ➢ Measuring Problem Solving
- ➢ Teaching Problem Solving
  1. Experts & Novices – Organizational Framework
  2. Useful & Not Useful Problems
  3. Implementation & Scaffolding
     - Coaching and Groups
     - Role for Computers
- ➢ Building a computer coach to enhance student metacognition
- ➢ Some Results





The Nature of Science is Problem Solving

“All science is either physics or stamp collecting
(quantitative problem solving) (cataloging information).”

Every science requires quantitative problem solving based on a universal set of fundamental principles

Awarded the 1908 Nobel Prize in Chemistry

“I must confess I am very startled at my metamorphosis into a chemist.”

Ernest Rutherford

In science, concepts are invented to solve problems.

- How do the Sun, Moon, Stars, Planets move around the Earth?
- How does an arrow fly through the air?
- How can an atom be stable?
- What happened to the antimatter in our Universe?

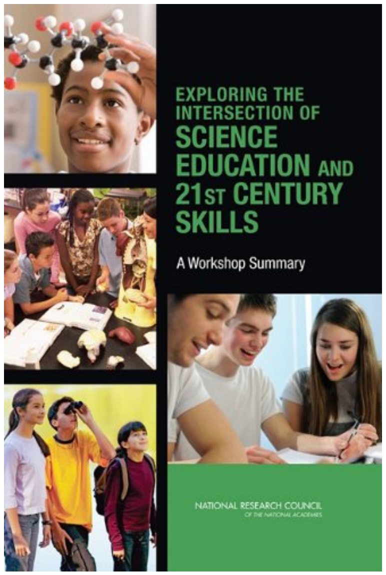
Those concepts are connected by a theoretical framework that can be used to solve other problems and uncovers new problems.

Problem solving is a complex and creative process of decisions connecting what you know to what you don’t.

To be science, problem solving is constrained by certain rules

- Logic
- Mathematics
- Testability
- Consistency
- Universality

Problem Solving is Necessary



NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES (2010)

21st Century Skills

- **Adaptability:**
- **Complex communication/social skills:**
- **Self-management/self-development:**
- **Systems thinking:**
- **Nonroutine problem solving:**

- **Diagnose the problem.**
- **Link information.**
- **Reflect on solution strategy.**
- **Switch strategy if necessary.**
- **Generate new solutions.**
- **Integrate seemingly unrelated information.**

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.

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

Accredited
ABET
Engineering Accreditation Commission

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

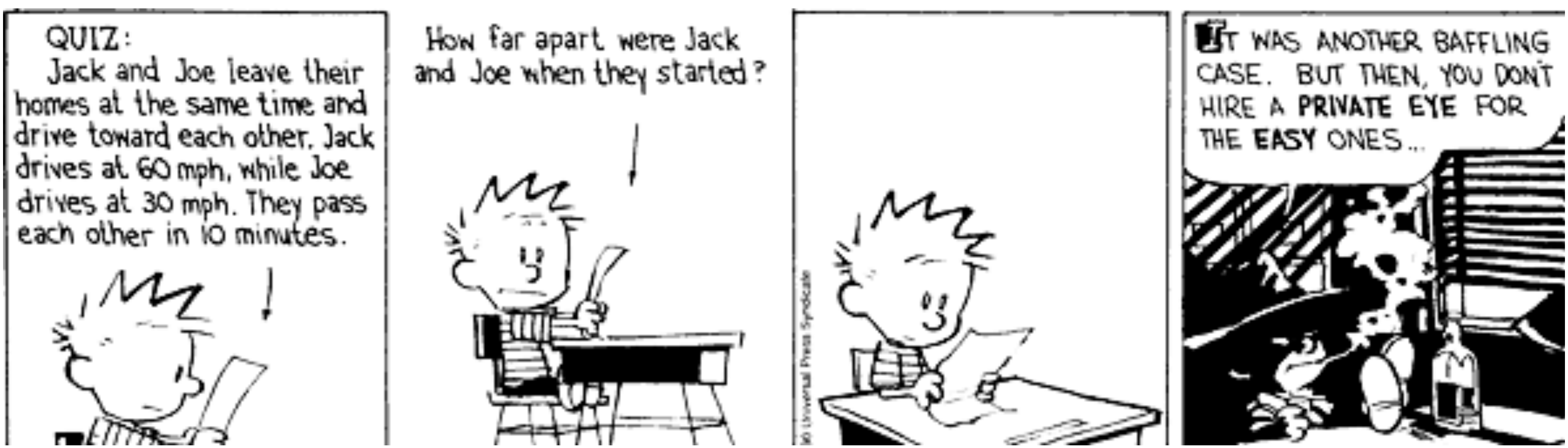
According to Cognitive Science

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.

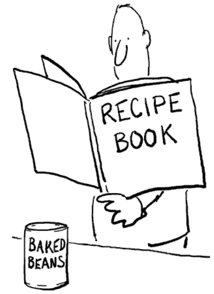
Solving a problem requires making decisions about connecting what you know in new ways.

M. Martinez, <u>Phi Delta Kappan</u>, April, 1998



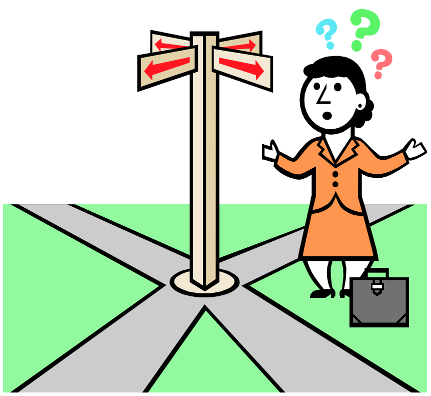
Solving Physics Problems

Expert: Solving a problem requires constructing a set of decisions that connects the situation to the goal using a few basic principles. All situations are approached the same way.



Novice: Solving a problem requires a following a recipe that connects the situation to the goal. Every type of situation has its own recipe.

Experts have an organized way of making decisions:



Doing this requires metacognition (active control of your thought processes)

- **Planning**
- **Monitoring**
- **Evaluating**

Novice Problem-solving Framework

STEP 1

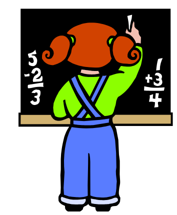
What Kind of Problem is This?

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.

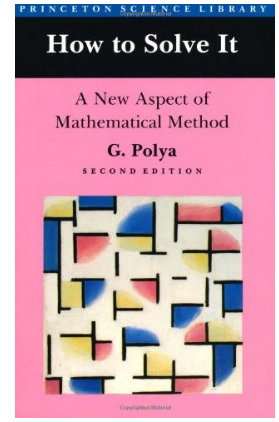
STEP 5

Is It Done?

Did I get an answer?

Problem-solving Framework
Used by experts in all fields

G. Polya, 1945



Not a linear sequence.
Requires continuous
reflection and iteration.

STEP 1 Recognize the Problem

What's going on and what do I want?

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.

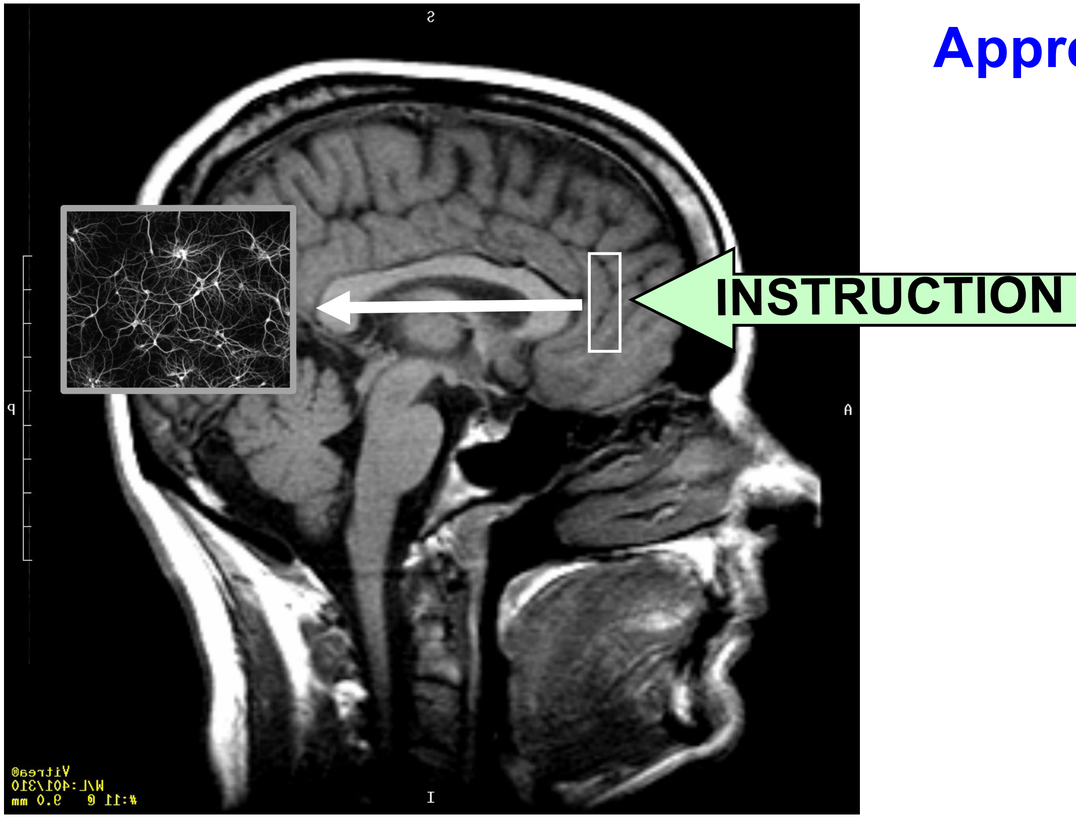
STEP 5 Evaluate the solution

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, 2012

Learning is Too Complex to Predetermine



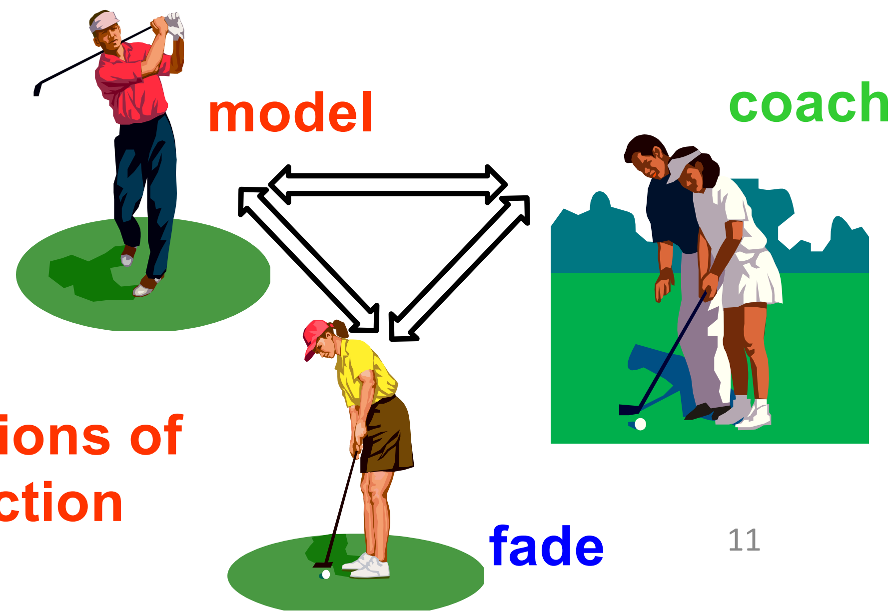
Brain MRI from Yale Medical School
Neuron image from Ecole Polytechnique Lausanne

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?



Collins, Brown, & Newman (1990)

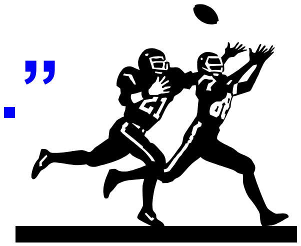
3 primary functions of effective instruction

Metacognition Can Be Learned If It Is Practiced

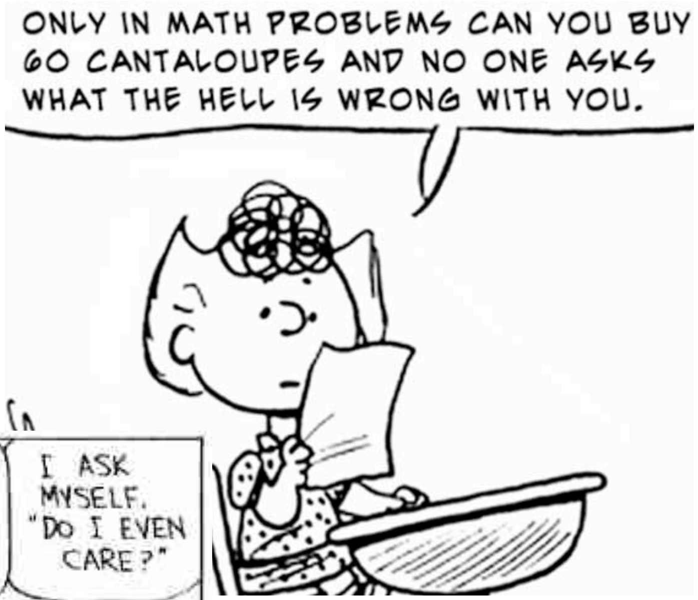
BUT

"Practice does not make perfect.
Only perfect practice makes perfect."

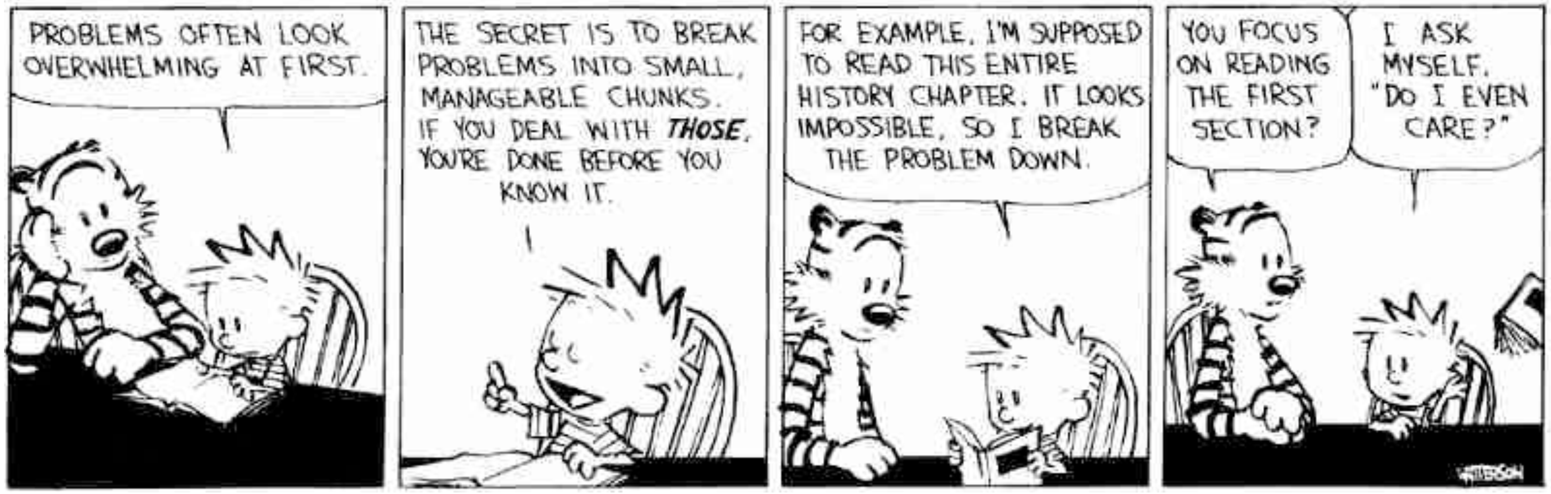
Vince Lombardi (expert on coaching)



Students need to practice on questions that are obviously (to them) reasonable and require reasonable decisions.



Making those decisions requires metacognition.
Metacognition requires motivation.



Subverting Problem Solving by Eliminating Metacognition

Any problem solution can be reduced to a recipe.

This often starts at the beginning of the course with the "Kinematics Equations"

Equation	x	a	v	v_0	t
$v = v_0 + at$	—	✓	✓	✓	✓
$x = \frac{1}{2}(v_0 + v)t$	✓	—	✓	✓	✓
$x = v_0 t + \frac{1}{2}at^2$	✓	✓	—	✓	✓
$v^2 = v_0^2 + 2ax$	✓	✓	✓	✓	—

Identify one unknown quantity and three known quantities.
Use the table to look up the equation that is the solution

Typical textbooks and "helpful" websites.

When we "derive" an equation to show an interesting relationship, students hear:

- **That equation we end with is what is important. It is the recipe.**
- **To succeed you must remember all those equations or worse remember the derivation.**

"Do we have to derive the formulas on the test?"

Subverting student problem solving is supported by allowing students to bring in their own "cheat sheet" to tests. List of recipes.

Many homework and test problems reduce the need for metacognition

Typical textbook problem

A basketball player jumps straight up for a ball. To do this, he lowers his body 0.300 m and then accelerates through this distance by forcefully straightening his legs. This player leaves the floor with a vertical velocity sufficient to carry him 0.900 m above the floor.

(a) Calculate his velocity when he leaves the floor.

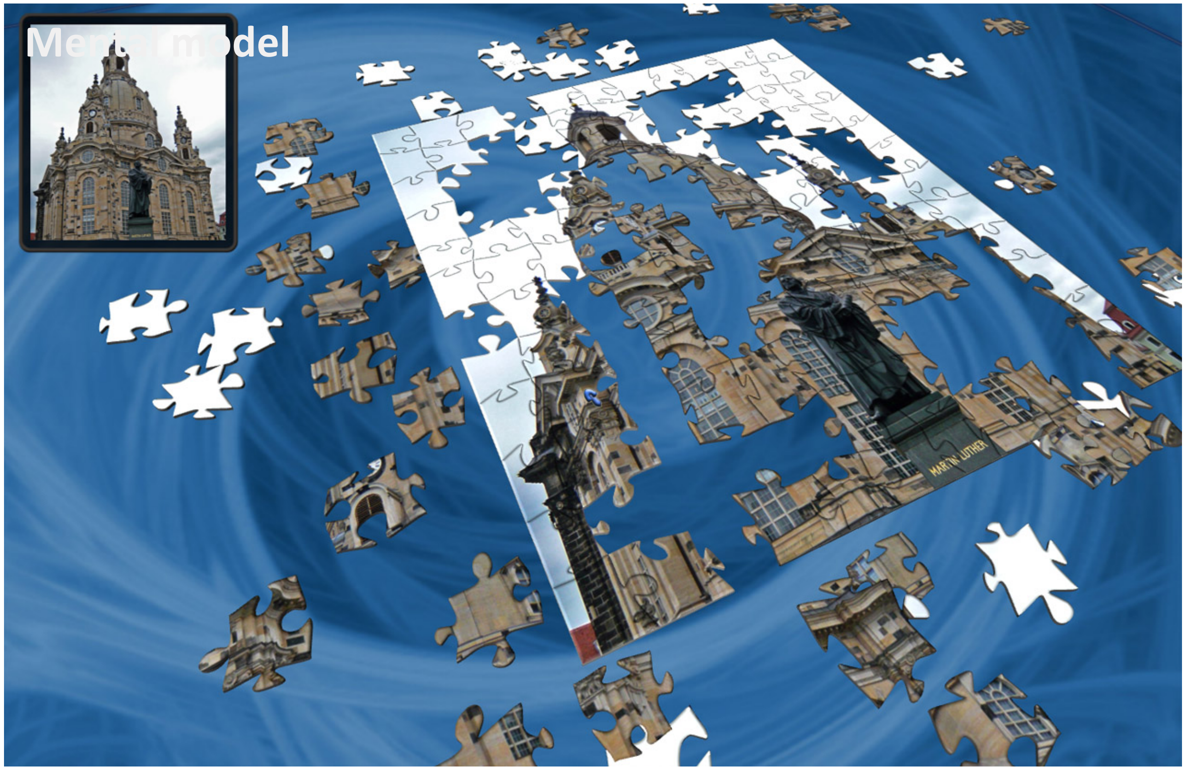
(b) Calculate his acceleration while he is straightening his legs. He goes from zero to the velocity found in part (a) in a distance of 0.300 m.

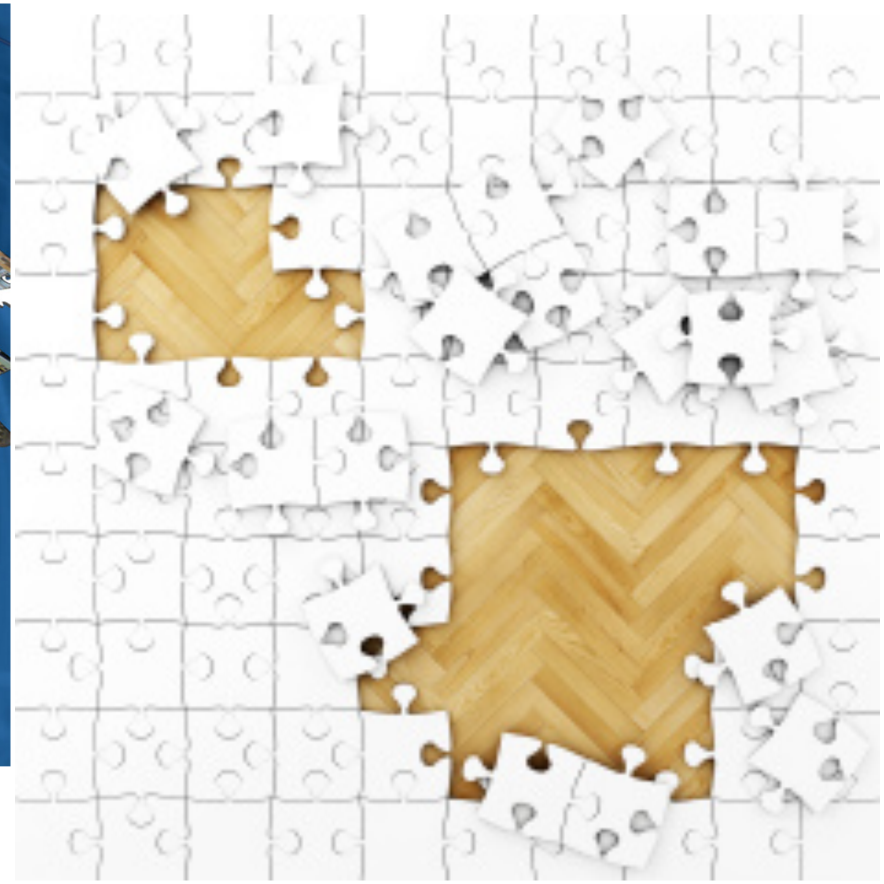
(c) Calculate the force he exerts on the floor to do this, given that his mass is 110 kg.

Change it so student has a chance to practice metacognition.

While watching a basketball game, you see the 80 kg center jump straight up to get a ball. It looks difficult and you wonder how strongly they have to push off. You noticed that just before the leap, the player's knees were bent which lowered their body 0.300 m. Then the player's legs rapidly straightened for the jump so their feet ended up 0.900 m above the floor.

Context-rich problem



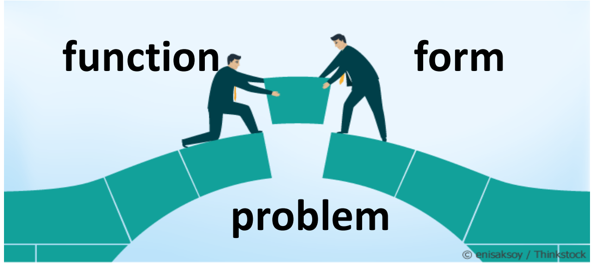


Context makes solving a problem easier.

Allows students to make connections to personal knowledge

The context only needs to be evocative of student reality

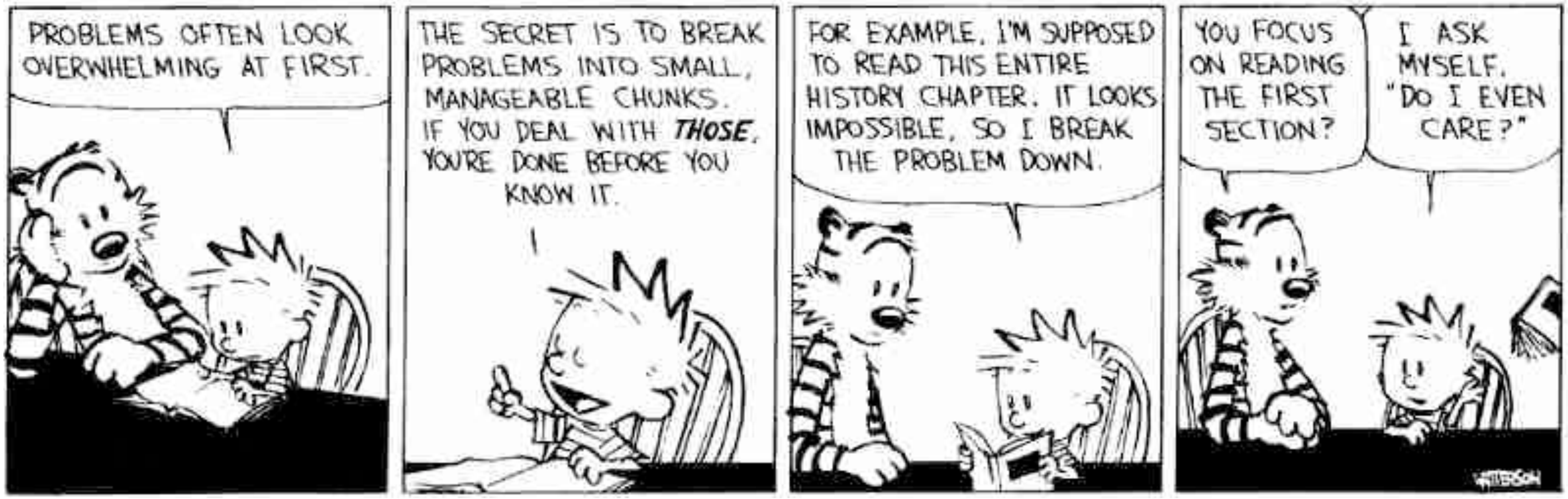
Problems Must Connect Form to Function



Students need to practice their greatest weakness: The desire not to make decisions

Types of decisions

- **Visualization: what is going on.**
- **Approximations: what can be neglected?**
- **Knowledge connection: what outside knowledge can I use?**
- **Organized decision making: what should be done next?**
- **Deciding on what physics to apply: what approach is most fruitful?**
- **Self-evaluation: how do I know if I am wrong?**
- **Utility: what has this got to do with me?**



Teaching Functions

Inexpensive:

Modeling (showing what to do, especially the decision making)

Fading (students attempting on their own as guidance is removed)

homework

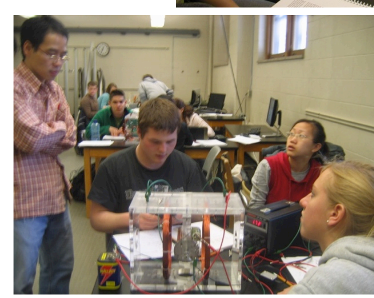
Expensive & Limited:

Coaching (students doing a task their way with fast feedback)

Instructor monitoring and intervention

- **Small class environment**
- **Cooperative groups for peer coaching**
- **Individual help**

Peer coaching

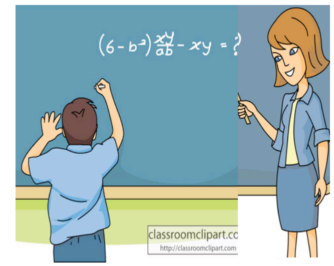


Instructor coaching groups

Tutoring

Computers as Supplementary Coaches?

Simulates an expert instructor's individual help



Takes a lot of time and patience

An office hour that supports student metacognition.

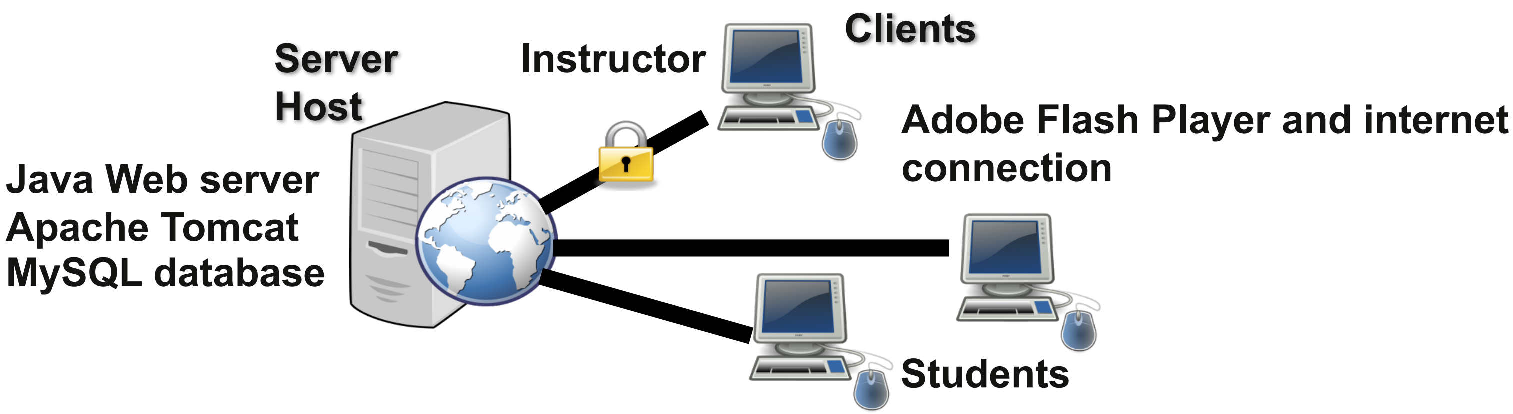
- Gets student to work on a specific problem.
- Asks questions to determine how the student is thinking.
- Allows student follow their own path even if it is not optimal
- Stimulates metacognition with "why" and "what would you do next" questions.
- Cuts off any incorrect path with appropriate questions.
- Determines if a certain skill is lacking and explicitly points it out.
- Finds alternative conceptions and tries to get students to recognize them.

A computer is not as flexible as an expert instructor but does have important advantages.

- Available on demand
- Infinitely patient
- Allows many student decisions
- Not threatening
- Much less expensive

Desired Properties of a Computer Coach

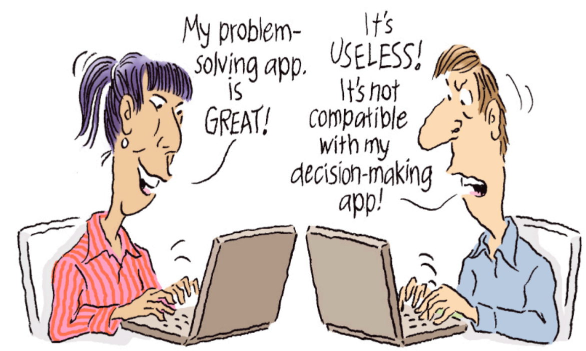
Available on demand: Use web to download coach from a database onto student's computer where it runs independent of server. Output saved to a database. Uses free software.



Intuitive computer interface cues student to make decisions within an expert-like problem solving framework that is necessary to solve the problem.

Decisions about

- **Objects**
- **Representations**
- **Physics principles**
- **Progression**



To be used, instructors must be able to modify the coach to fit their students & pedagogy without knowledge of underlying software. Instructor interface.

The Program Allows a Set of Decisions

Each decision

Leads to other decisions
Or
Uncovers part of the solution
Which
Leads to other decisions
Or
Uncovers part of the solution
Which
Leads to other decisions
Or
Uncovers part of the solution

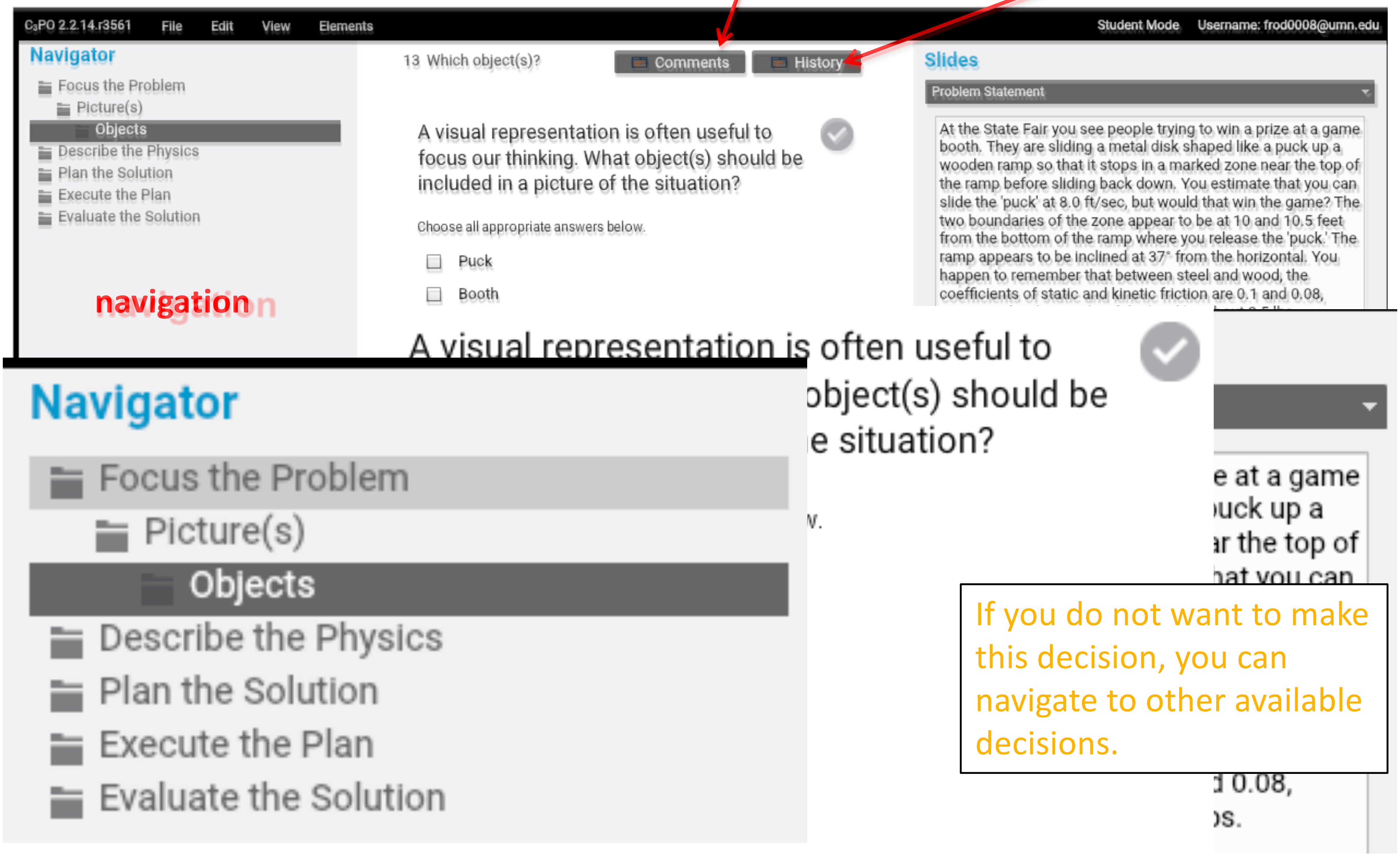
Decide how
parts of the solution
are combined
to answer the problem

-
-
-

Set in an expert-like problem solving framework

- **Focus**
- **Describe in Physics**
- **Plan**
- **Execute**
- **Evaluate**

Opening screen



Many Decisions

- **Focus – construct a useful picture (pictorial representation)**
  - **Objects**
  - **Point of view**
  - **Question to be answered**
  - **Useful times**
  - **Basic quantities (known or unknown?)**
  - **Necessary assumptions**

Directions
Magnitudes
Relationships to other quantities
Causality, forces, and interactions

- **Physics description - build equations (math representation)**
  - **Productive fundamental physics approaches (often more than 1 needed)**
    - **Kinematics**
    - **Forces (and torque)**
    - **Conservation of Energy**
    - **Conservation of Momentum**
    - **Conservation of Angular Momentum**

Useful diagrams
Useful coordinate system
Useful time intervals
Useful systems & states
Useful quantities
Useful facts (i.e. 3rd law, $F_f = \mu_k N$, KE = ½ mv^2)
Useful relationships & constraints

  - **Identify the target quantity or quantities that answers the question.**

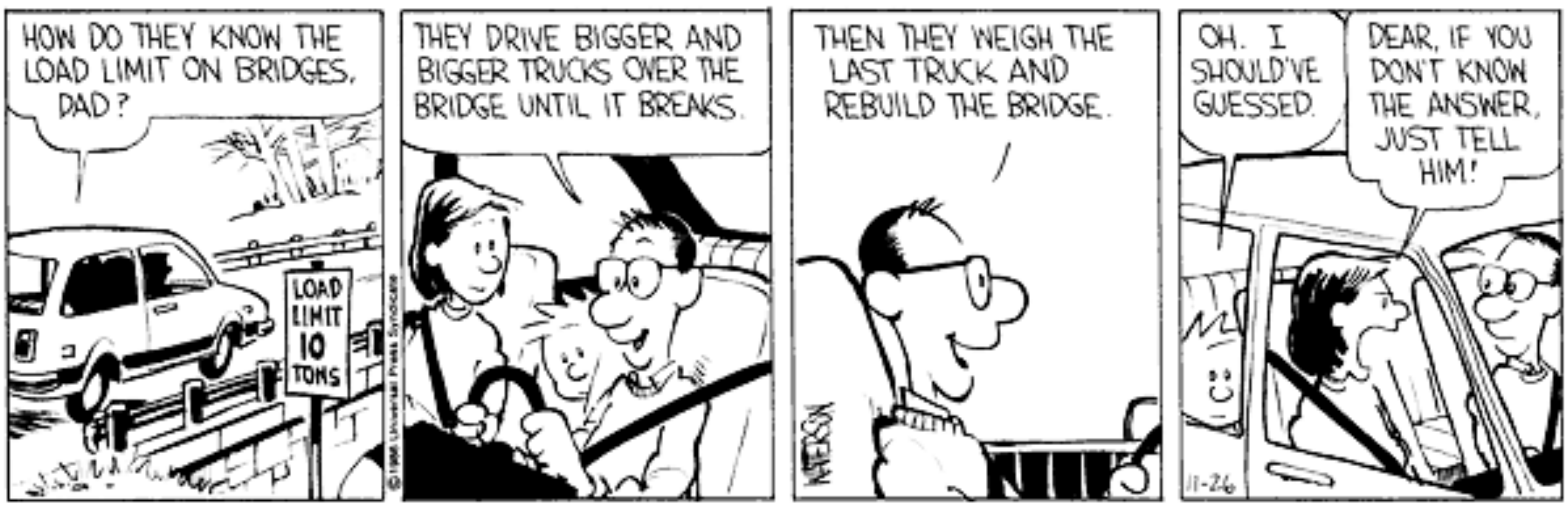
More Decisions

- **Plan – organize equations for mathematical solution**
  - **Use the constructed equations to get the target in a logical and organized manner**
  - **Determine if more information is necessary**
  - **Determine if another approach is necessary**

Cycle back to
Focus
Describe

- **Execute the plan – do the algebra constructed in the plan**
  - **Give the algebraic solution**
  - **Then give the numerical solution if necessary.**

Do the math with pencil and paper by following the plan.



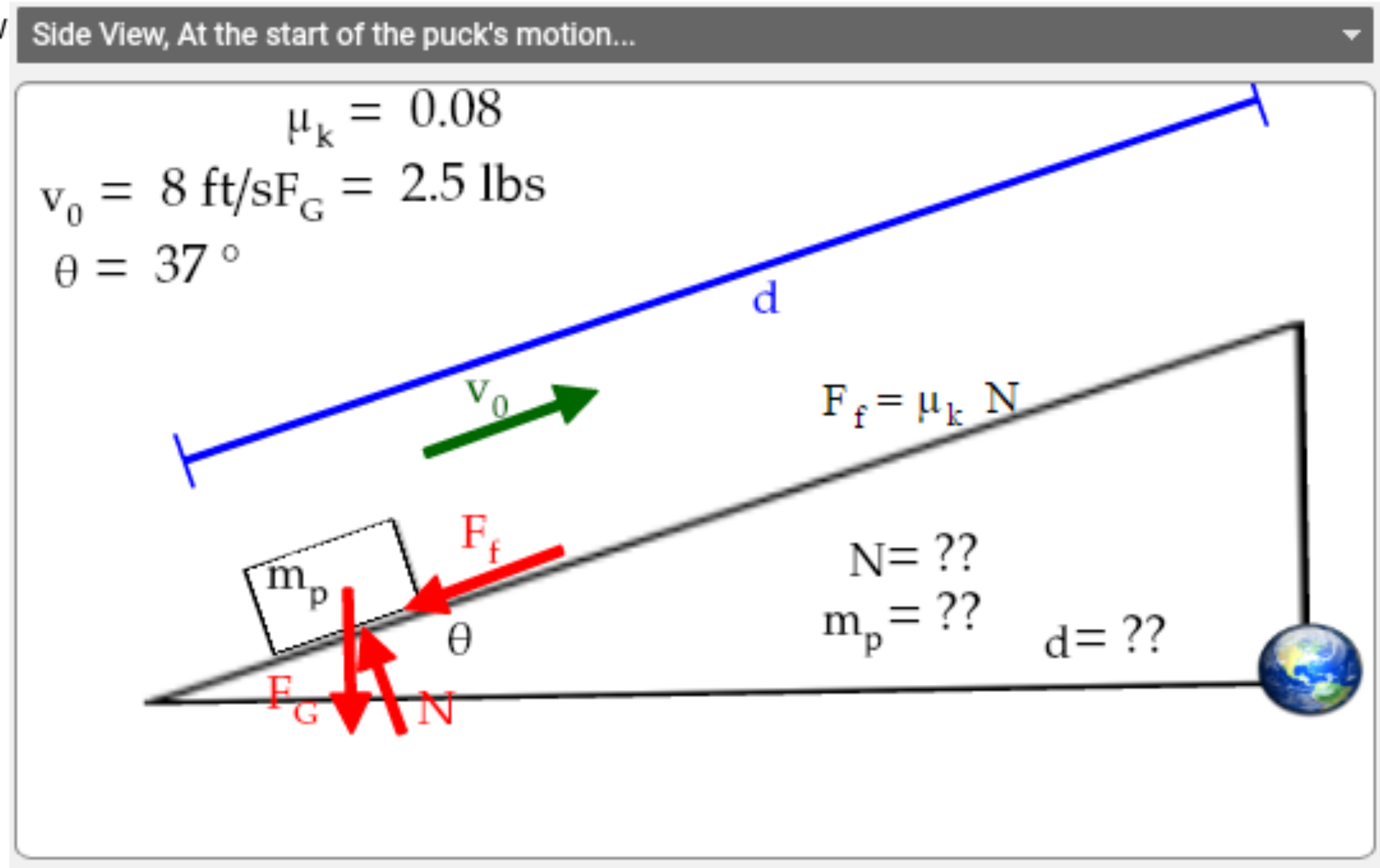
Taking the default path

Picture after many choices

What type of quantity do you w

Choose one.

- ○ Time
- ○ Position
- ◉ Length
- ○ Velocity
- ○ Acceleration
- ○ Force
- ○ Mass
- ○ Angle
- ○ Coefficient of Friction
- ○ I am done.



Decisions need to be made for each quantity. These quantities are added to the picture when they are chosen.

If more quantities are needed as you progress, the coach will ask you to specify them when they are needed.

Not Taking the default path

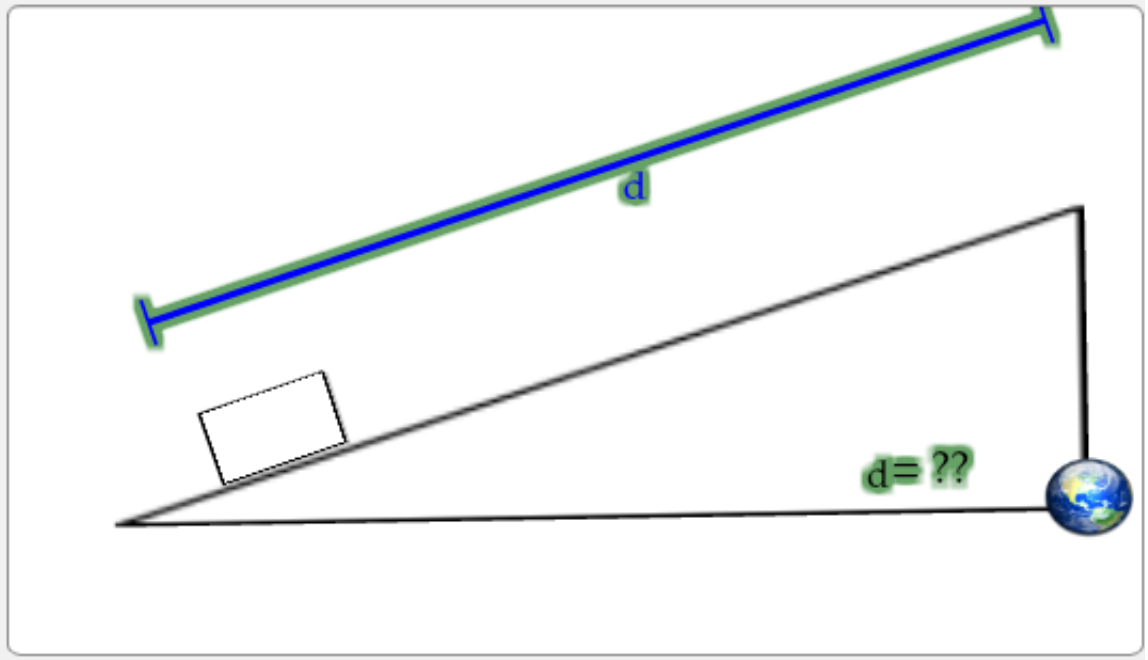
What question is the problem asking you to determine?

Choose one.

- ◯ What is the mass of the puck?
- ◉ Is the final distance the puck travels up the ramp between 10 and 10.5 feet?
- ◯ What initial velocity of the puck is needed to win the game?

Picture "fills" as decisions are made

Side View, At the start of the puck's motion...



What is the distance that the puck travels wh
ramp?

Choose one.

- ◯ 8 ft
- ◯ Somewhere between 10 and 10.5 feet.
- ◯ 32 ft
- ◉ Unknown, but calculable.
  YES
- ◯ Unknown and arbitrary.

Another Major Decision

Which approach do you wish to use?

Choose one.

- Kinematics
- Forces
- Conservation of Energy
- Conservation of Momentum
- Conservation of Angular Momentum

This particular coach is set to allow any of the first 3, although all are possible solution paths.

You will need 2 of them to solve this problem

Which equation best represents the conservation of energy relationship?

Choose one.

- ○ $\Sigma F = m\,a$
- ◉ $E_f - E_i = E_{in} - E_{out}$

  Yes. The difference between the final and initial system energy is equal to the difference between the energy input to the system and the energy output from the system.
- ○ $K - U = 0$

Instructor can easily change the wording, the symbols, and the feedback.

To use conservation of energy, you first must identify the system of interest. Which object(s) do you want to include in the system?

Choose one.

- ◉ Puck alone

  OK
- ○ Puck+Ramp
- ○ Puck+Earth
- ○ Puck+Ramp+Earth

Now specify

Initial & final time

Coordinate system

System energy at initial time

System energy at final time

Energy transfers

After many decisions, get the following information

$$F_f = \mu_K\, N$$

$$F_G = m_p\, g$$

Approach Eqns

$$0 - \frac{1}{2} m_p\, v_0^{\,2} = 0 - \left(F_f + F_G \sin\theta\right) d$$

Target: d

Unknowns: a, m_p, N, F_f

Decide there is not enough information – decide on adding another approach

Results

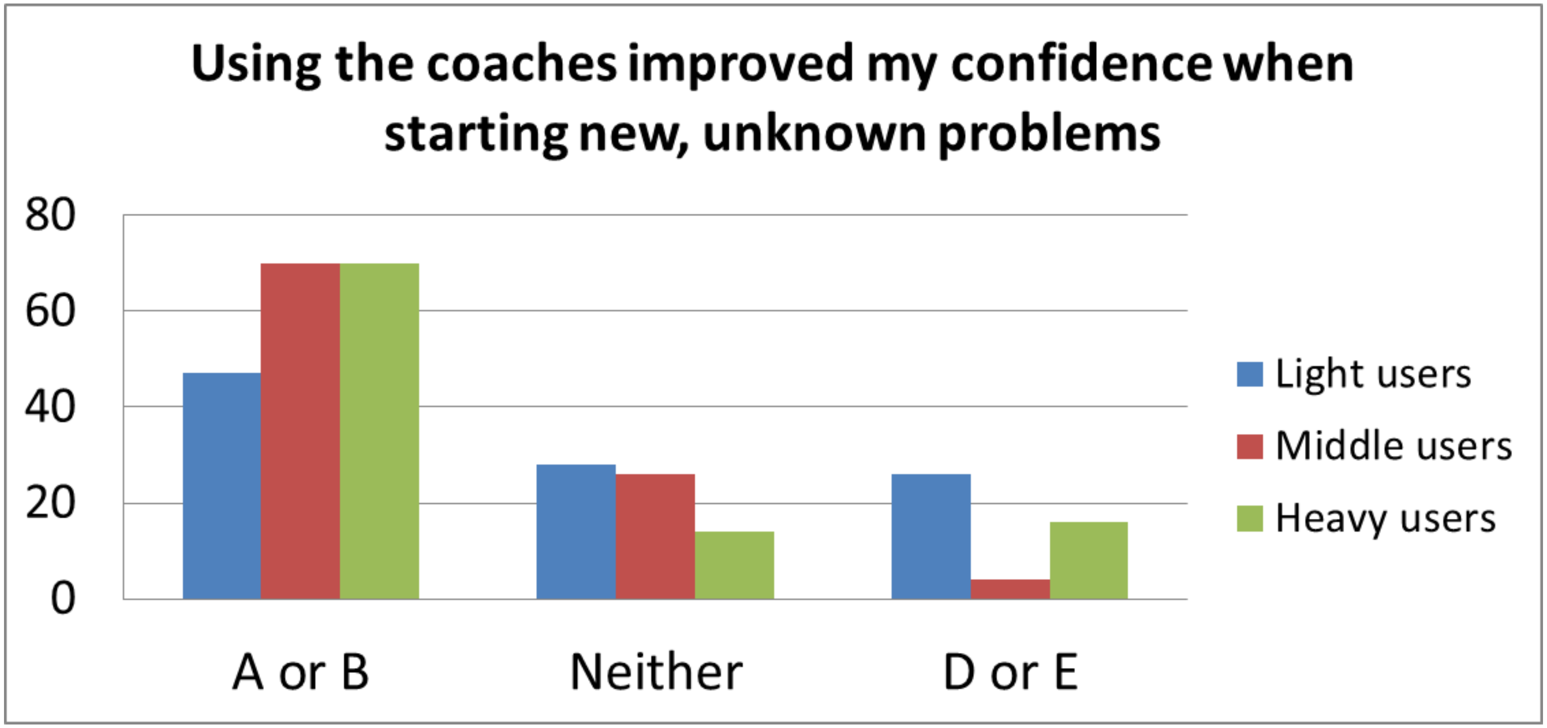
Tested v 1.0 in large calculus based intro. physics classes.

- **Students thought the coach was initiative and easy to use**
- **Students thought the coach improved**
  - **Problem solving confidence**
  - **Conceptual understanding**
  - **Problem solving skills**
- **Students found the coaches attractive**
  - **When equal credit for using WebAssign or completing a coach, students averaged 80% coach use.**
  - **When given no credit for using the coaches**
    - **~ 1/3 of the class used > 75% of the coaches (H)**
    - **~ 1/3 of the class used 35% - 65% of the coached (M)**
    - **~ 1/3 of the class used < 25% of the coaches (L)**

PHYSICAL REVIEW PHYSICS EDUCATION RESEARCH 12, 010105 (2016)

Ryan, Frodermann, Heller, Hsu, and Mason

Do students find coaches useful?

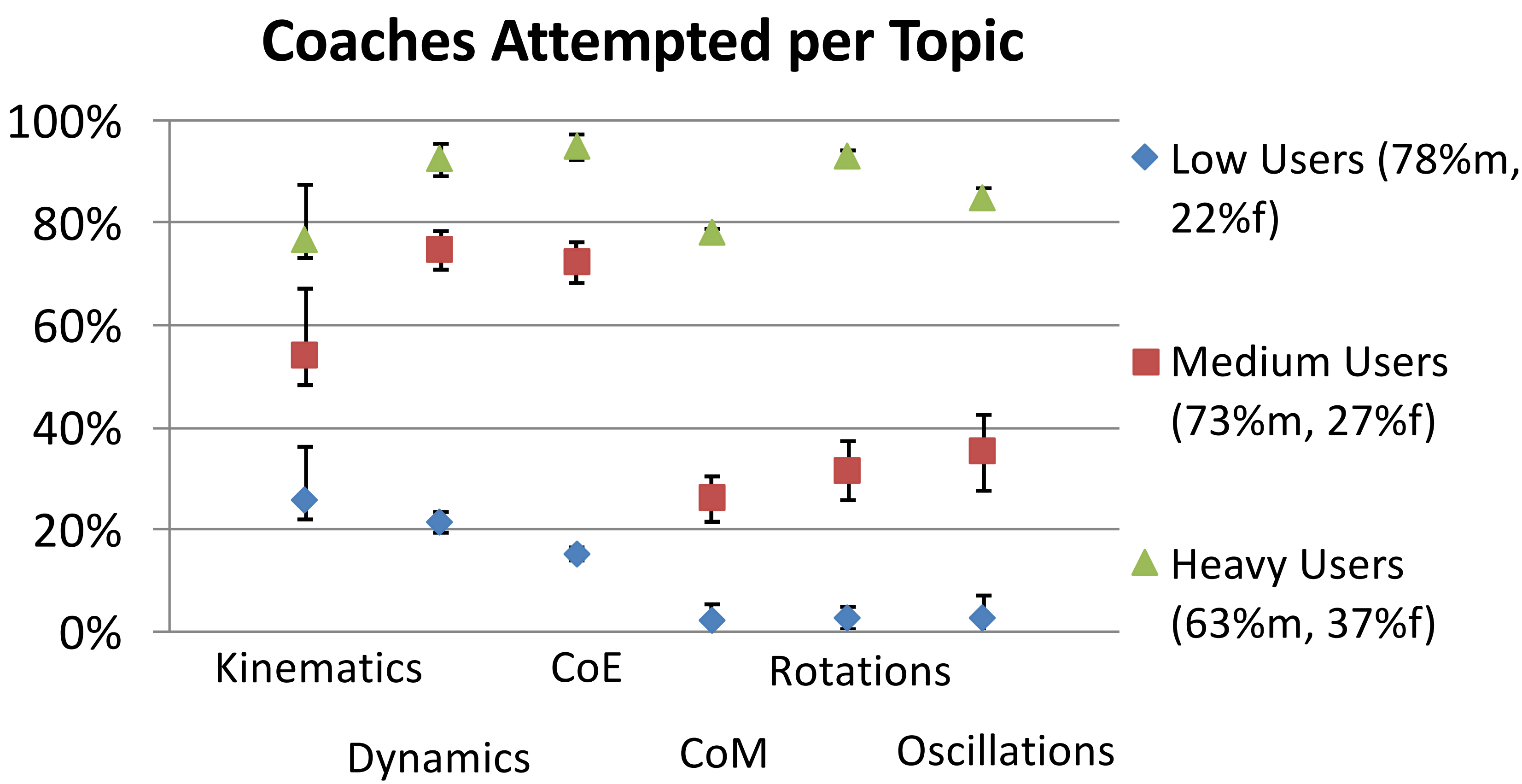


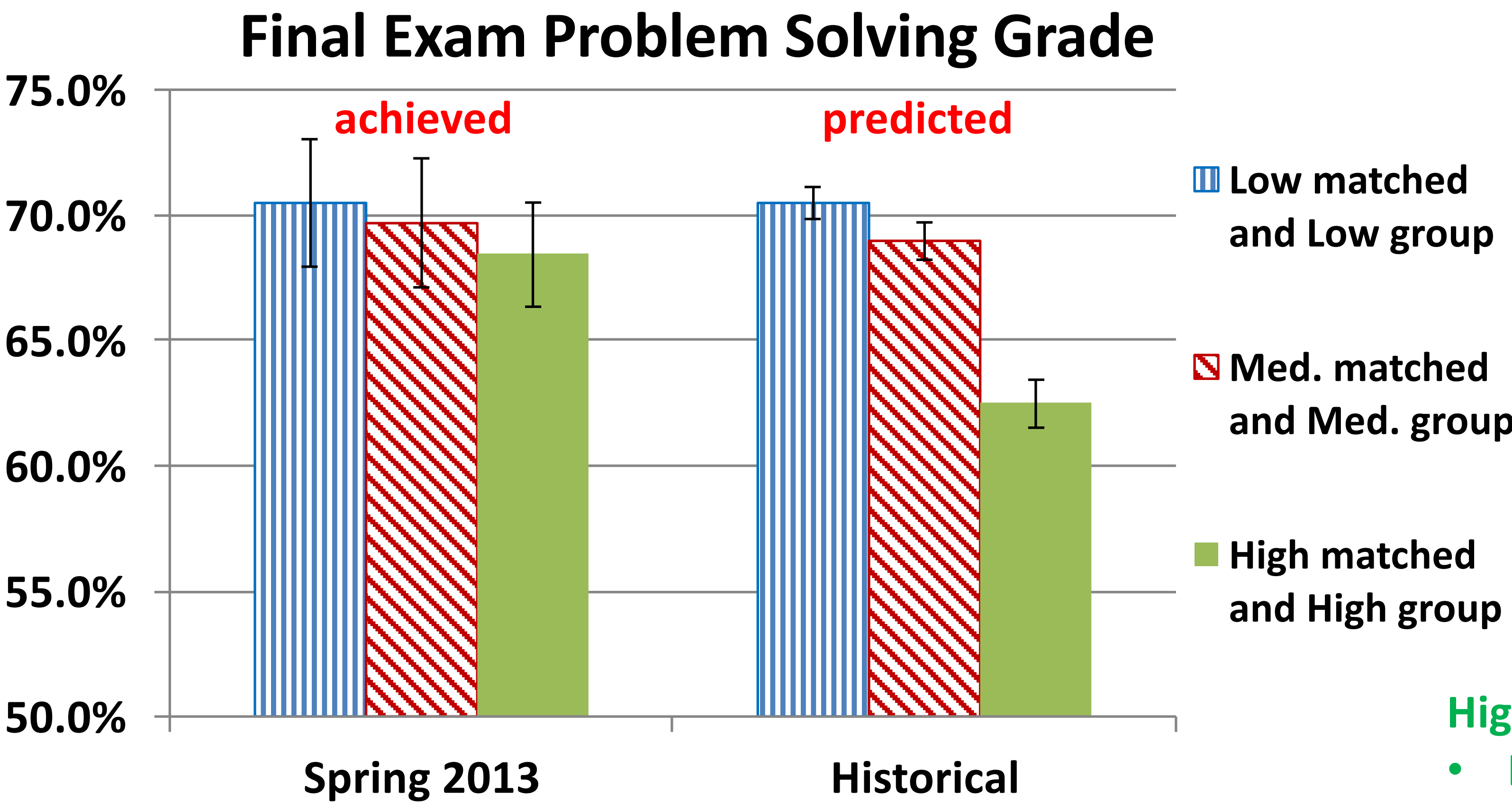
A: Strongly agree **B:** Agree **C:** Neither **D:** Disagree **E:** Strongly disagree

Student Coach Use

- **Track total # of coaches attempted during Spring 2013**
  - **(N = 251, 70% m, 30% f)**
- **Three groups identified for further study:**

L = light user: 0-25%	**N_L = 59 (29% of N)**
M = medium user: 35-65%	**N_M = 40 (15% of N)**
H = heavy user: 75-100%	**N_H = 43 (20% of N)**





Tested against expert problem solving rubric

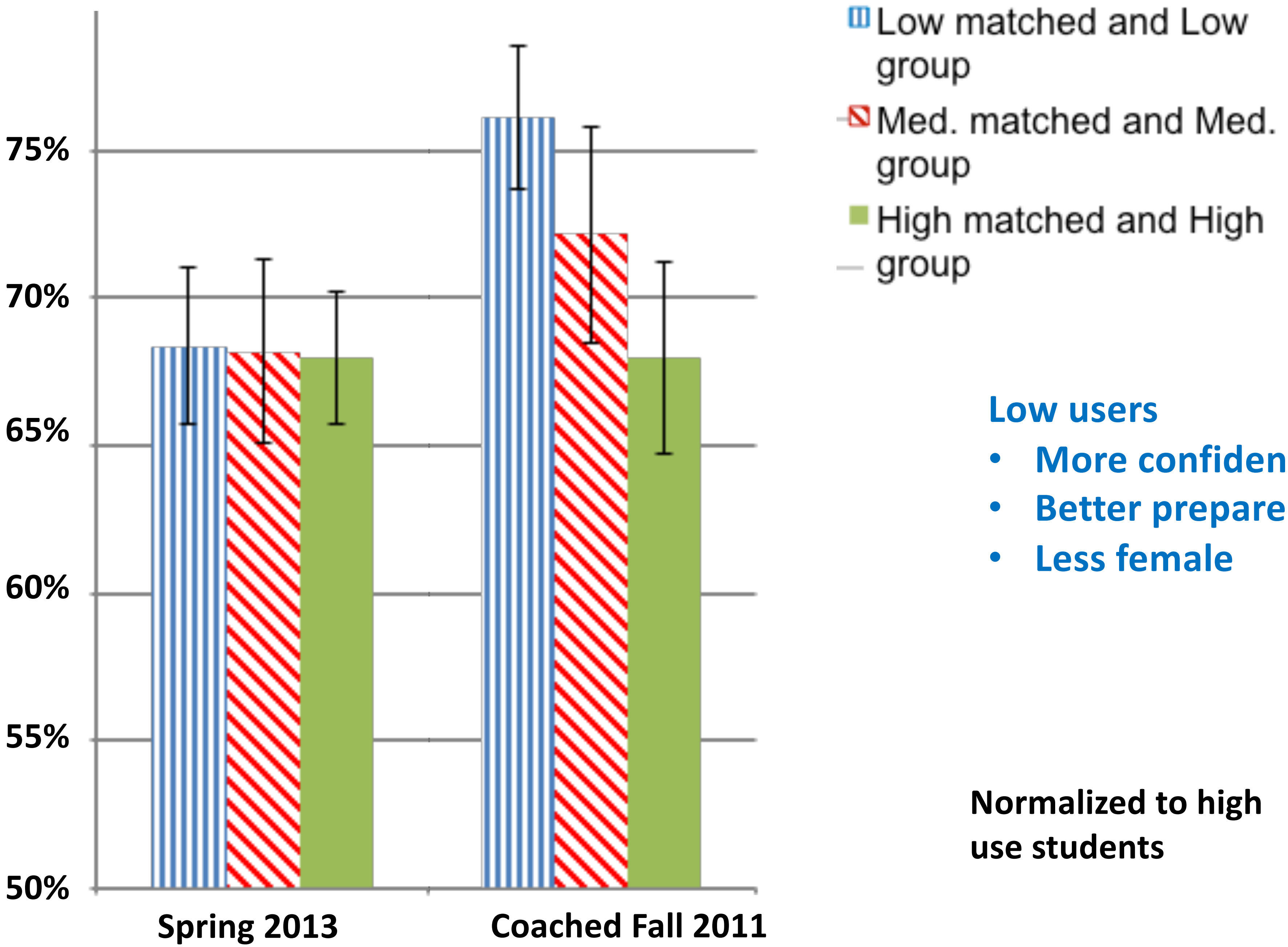
High users

- Less confident
- Less well-prepared
- More female

Propensity Analysis

- Historical is a 4 to 1 match of Coached Spring 2013 students from 3400 previous non-coached students. (multiple randomized matching trials)
  - Matched on pre-class FCI, gender, expected grade, and expected study time.
  - ~ 85% student perfect match.
  - Final exams normalized from Low Users and Low users matched.
- The 6% ± 3%, difference between High Users ($p < 0.05$).
  - This is 1/2 of a letter grade.

Effectiveness for low use students

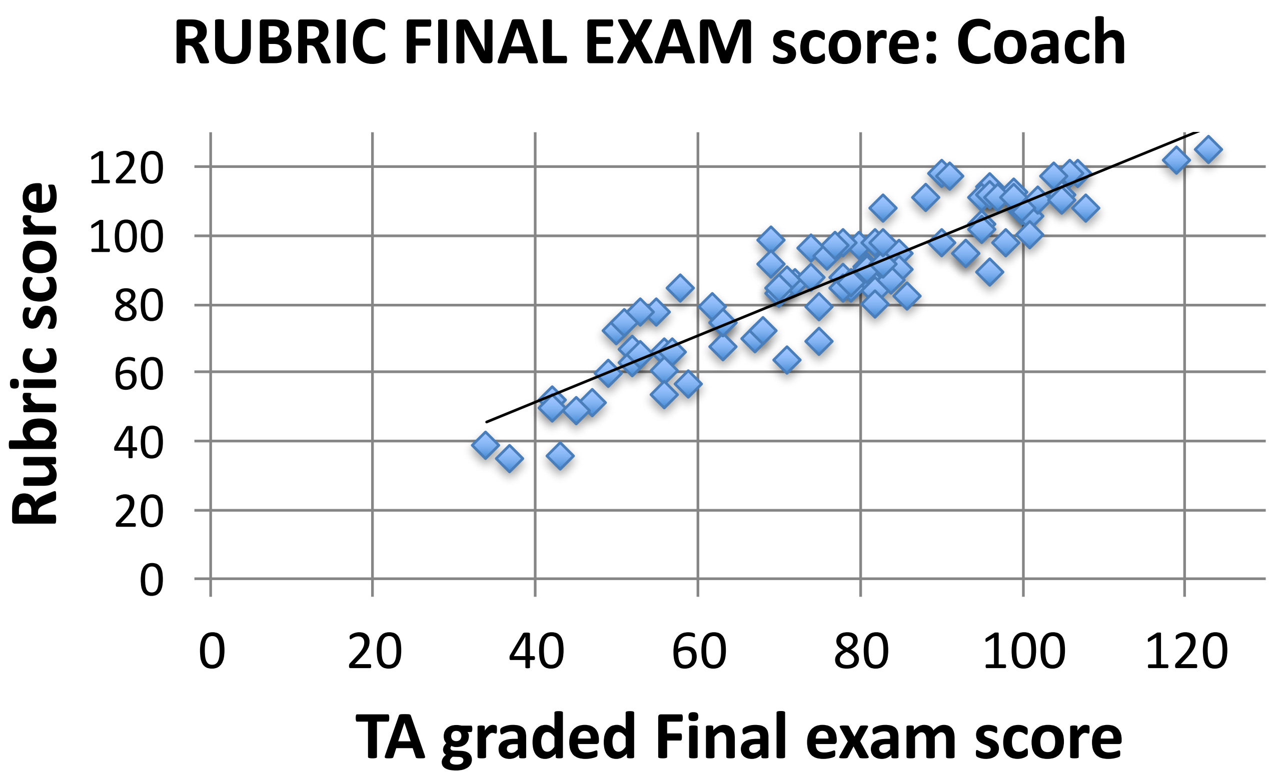


Low users

- **More confident**
- **Better prepared**
- **Less female**

Normalized to high use students

TA grading vs. Rubric



Combined Final exam problems:
correlation = 90%
Individual Problems:
Correlation = 80%

- **The TA grades are highly correlated with independently assessed rubric scores.**
  - **Note: Our TAs have gone through TA training in the Minnesota model but not the rubric assessment.**

Structure of problem solving rubric

SCORE ←

CATEGORY: (based on literature)	5	4	3	2	1	0	NA (P)	NA (S)
Useful Description								
Physics Approach								
Specific Application								
Math Procedures								
Logical Progression								

Want

- **Minimum** number of categories with relevant aspects of problem solving
- **Minimum** number of scores with enough information to improve instruction

Rubric Scores (in all categories)

5	4	3	2	1	0
Complete & appro-priate	Minor omission or minor errors	Parts missing and/or contain errors	Most missing and/or mostly errors	All inappro-priate	No evidence of category

NOT APPLICABLE (NA):

NA - Problem	NA - Solver
Not necessary for this problem *(i.e. visualization or physics principles given)*	Not necessary for this solver *(i.e. able to solve without explicit statement)*

Docktor et al, Physical Review PER (submitted)

Version 2 Coaches

- **Customizable Computer Coaches for Physics Online (C3PO)**
  - **Authoring tool for coaches.**
    - **Hard edits are now "easy". Impossible edits are now possible.**
  - **Changed architecture from script to true object-oriented code.**
    - **This allows a much larger range of freedom for both students and instructors.**
  - **Student interface is very similar to version 1.**
    - **New interactions through drag/drop interactions.**
  - **Instructors now have an interface.**
    - **No programming languages needed. The instructor coach construction is through a Graphical User Interface.**
      - **"LabView" for coach design.**

We are now collaborating with faculty from:

Ohio State University, Central Michigan University, University of Wisconsin Platteville, College of DuPage, Normandale Community College, University of Minnesota Rochester

Real Problem Solving Requires Metacognition

- **Students do not normally practice metacognition when trying to solve a physics problem.**
- **Students need modeling, coaching, and fading to learn problem solving.**
- **Students need to practice on problems that require metacognition.**
- **It is possible that computers can be a part of this process by being personal metacognition coaches to help students solve physics problems.**

To Try v1.0 Coaches Visit

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

Or Google PER Minnesota

The superior leader (teacher) gets things done with very little motion. He imparts instruction not through many words but through a few deeds. He keeps informed about everything but interferes hardly at all. He is a catalyst, and though things would not get done well if he weren't there, when they succeed he takes no credit. And because he takes no credit, credit never leaves him.

A leader (teacher) is best when people barely know he exists, not so good when people obey and acclaim him, worst when they despise him. But of a good leader (teacher), who talks little, when his work is done, his aim fulfilled, they (students) will say, 'We did this ourselves.'

Lao Tse, *Tao Te Ching (580-500 B.C.E.)*

Lao-Tse is considered the first philosopher of the Taoist school. The Te-Tao Ching, attributed to Lao-Tse, is one of the most sacred texts of Taoism.

Minnesota PER group reunion
@ AAPT S14
18 years of alumni who contributed to this research.

The best is the enemy of the good.

"le mieux est l'ennemi du bien"

Voltaire

Please visit our website for more information:

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