Teaching Physics Through Problem Solving

“I understand the concepts, I just can’t solve the problems.”

Ken Heller
School of Physics and Astronomy
University of Minnesota

15 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 Group - P. Heller and graduate students

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

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

• Write down what you want from this presentation.
• Form a group of 3.
• Decide on the single most important information you want from this presentation.
• TIME ALLOTTED
  10 minutes
• PROCEDURES
  Formulate a response individually.
  Discuss your response with your partners.
  Listen to your partners' responses.
  Create a new group response through discussion.
AGENDA
A Guide for Discussion

- Who are the Students
- What Is It
  - Course structure
- What are Problems
  - is Problem Solving
- How to Teach It
- Does It Work
  - Data
Algebra Based Physics Students
300 students/term

Interest

Architecture 45%
Paramedical 26%
  Physical therapy
  dentistry
  pharmacy
  chiropractic
  medical tech
  veterinary
Agriculture / ecology 9%

equal female / male
50 % had calculus
40 % had chemistry
50% had high school physics

30% freshman
30% sophomore
30% junior
10% senior
# Physics for Biology Majors
600 students/term

## Majors

<table>
<thead>
<tr>
<th>Major</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological Science</td>
<td>49%</td>
</tr>
<tr>
<td>Allied Health</td>
<td>19%</td>
</tr>
<tr>
<td>Social Science</td>
<td>7%</td>
</tr>
<tr>
<td>Architecture</td>
<td>3%</td>
</tr>
<tr>
<td>Engineering</td>
<td>2%</td>
</tr>
<tr>
<td>Other</td>
<td>20%</td>
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<tr>
<td>+ Pre-Med</td>
<td>37%</td>
</tr>
</tbody>
</table>

## Class Year Distribution

- **Freshman**: 7%
- **Sophomore**: 38%
- **Junior**: 19%
- **Senior**: 17%

## Gender Distribution

- **Male**: 39%
- **Female**: 61%

## Pre-requisites

- **Had U. Calculus**: 71%
  - (Had HS Calculus): 50%
- **Had HS Physics**: 71%

## Other

- **Expect A**: 48%
- **Work**: 74%
- **Work more than 10 hrs/wk**: 50%
# Calculus Based Physics

1200 students/term

<table>
<thead>
<tr>
<th>Majors</th>
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<tbody>
<tr>
<td>Engineering</td>
<td>75%</td>
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<tr>
<td>Physics/Astro</td>
<td>5%</td>
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<tr>
<td>Chemistry</td>
<td>6%</td>
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<tr>
<td>Mathematics</td>
<td>5%</td>
</tr>
<tr>
<td>Biology</td>
<td>9%</td>
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</tbody>
</table>

| Male                  | 79%   |
| Had Calculus          | 80%   |
| Had HS Physics        | 87%   |
| Freshman              | 64%   |
| Sophomores            | 22%   |
| Juniors               | 10%   |

| Expect A              | 61%   |
| Work                  | 53%   |
| Work more than 10 hrs/wk | 25% |
**TASK**
Discuss why you assign problems in physics courses.

List the common goals of the problems.

**TIME ALLOTTED**
5 minutes

**PROCEDURES**
Form a group of 3 people
Choose one person as a recorder

*Formulate* a response individually.
*Discuss* your response with your partners.
*Listen* to your partners' responses.
*Create* a new group response through discussion.
Should Teaching Problem Solving be an Aim of Introductory Physics?

◆ What do Other Departments Want?
◆ What is Useful?
◆ Is it Needed?
◆ Is it Physics?
### Employment

<table>
<thead>
<tr>
<th>Skill</th>
<th>Private Sector</th>
<th>Gov’t Labs</th>
<th>High Schools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem Solving</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Interpersonal Skills</td>
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<td>Technical Writing</td>
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<td>Management Skills</td>
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<tr>
<td>Adv. Computer Skills</td>
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<td></td>
<td></td>
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<tr>
<td>Business Principles</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Statistical Concepts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knowledge of Physics</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Advanced Mathematics</td>
<td></td>
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</tbody>
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Survey of Physics Bachelors, 1994-AIP
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 Real world application of mathematical concepts and techniques

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

Modified survey in response to CBS Curriculum Committee
What Is Problem Solving?

“Process of Moving Toward a Goal When Path is Uncertain”

• If you know how to do it, it’s not a problem.

Problems are solved using tools

General-Purpose Heuristics

Not algorithms

“Problem Solving Involves Error and Uncertainty”

A problem for your student is not a problem for you

Exercise vs Problem

M. Martinez, Phi Delta Kappan, April, 1998
Solving Problems Requires Conceptual Knowledge:
From Situations to Decisions

- Visualize situation
- Determine goal
- Choose applicable principles
- Choose relevant information
- Construct a plan
- Arrive at an answer
- Evaluate the solution

Students must be taught *explicitly*

The difficulty -- major misconceptions, lack of metacognitive skills, no heuristics
Some Reflective Skills (Metacognition)

- Managing time and direction
- Determining next step
- Monitoring understanding
- Asking skeptical questions
- Reflecting on own learning process

Some General Tools (Heuristics)

- Means - Ends Analysis (identifying goals and subgoals)
- Working Backwards (step by step planning from desired result)
- Successive Approximations (idealization, approximation, evaluation)
- External Representations (pictures, diagrams, mathematics)
- General Principles of Physics

M. Martinez, Phi Delta Kappan, April, 1998
Procedure for Change

<final | T | initial>

Transformation Process

Initial State of Learner

Curriculum Instructional Framework

Paths

Barriers

Desired Final State of Learner

Instructor

F. Reif (1986)
Phys. Today 39
Cognitive Apprenticeship Instruction

Learning in the environment of expert practice

Course Structure

**LECTURES**
*Three hours* each week, sometimes with informal cooperative groups. *Model constructing knowledge, model problem solving framework.*

**RECITATION 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 two weeks.
Problem 2

Question: how far away from the tree does the fruit and arrow combination land?

Approach: use conservation of momentum and kinetic energy. Assume constant acceleration due to gravity. Ignore air resistance and friction.

Initial State

Plan the Solution:

\[ d = V_{xf}t + \frac{1}{2}at^2 \]
\[ V_{xf} = \frac{m_1V_0}{m_1+m_2} \]
\[ V_{x0} = V_0 \cos \theta \]
\[ t = \sqrt{\frac{2h}{g}} \]
\[ d = \frac{m_1}{m_1+m_2} V_0 \cos \theta \sqrt{\frac{2h}{g}} \]

Check Units:

\[ m = \frac{m_1}{m_1+m_2} \]
\[ n_1 = \left( \frac{m_1}{m_1+m_2} \right)^3 \]
\[ m = m_1 \to OK \]

Is the answer complete?

Yes, the distance was found in terms of the requested values.

Is the answer reasonable?

Yes, the units check out ok, and \( d \) will be smaller than \( h \) due to conservation of energy.

Is the answer correctly stated?

Yes, it is in units of distance, meters.
Gain on FCI

Pretest (Percent)

Gain (Percent)

ALS

SDI

WP

Full Model

UMn Cooperative Groups

UMn Traditional

ASU(nc)

ASU(c)

WP*

PI(HU)

HU
Initial State of the Learner

Students have Misconceptions about

- The Field of Physics
- Learning Physics
- Nature
- Problem-solving

All combine to make it difficult for students to solve problems.

Not the same as “getting a problem right”.
Students’ Misconceptions About Problem Solving

You need to know the right formula to solve a problem:

- Memorize formulas
- Bring in "crib" sheets
- Memorize solution patterns

It's all in the mathematics:

- Manipulate the equations as quickly as possible
- Plug-and-chug

Numbers are easier to deal with:

- Plug in numbers as soon as possible
How do YOU solve a problem?

- Read the next problem
- Write down how you would go about solving this problem

TIME ALLOTTED - 5 minutes

Form a group of 3 people
Assign one person to be the recorder.

Discuss your thoughts with your partners.
Create a group response through discussion.

PRODUCT
A list of individual similarities and differences and a list of your recommend elements of problem solving
You are investigating the possibility of producing power from fusion. The device being designed confines a hot gas of positively charged ions, called a plasma, in a very long cylinder with a radius of 2.0 cm. The charge density of the plasma in the cylinder is $6.0 \times 10^{-5}$ C/m$^3$. Positively charged Tritium ions are to be injected into the plasma perpendicular to the axis of the cylinder in a direction toward the center of the cylinder. Your job is to determine the speed that a Tritium ion should have when it enters the cylinder so that its velocity is zero when it reaches the axis of the cylinder. Tritium is an isotope of Hydrogen with one proton and two neutrons. You look up the charge of a proton and mass of the tritium in your Physics text and find them to be $1.6 \times 10^{-19}$ C and $5.0 \times 10^{-27}$ Kg.
How Do You Solve This

An infinitely long cylinder of radius $R$ carries a uniform (volume) charge density $\rho$. Use Gauss’ Law to calculate the field everywhere inside the cylinder.

Compare procedures with the previous problem.

Which motivated you to practice the most elements of expert problem solving?

Textbook Problem
Problem-solving Framework
Used by experts in all fields

STEP 1
Recognize the Problem
What's going on?

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 out of this?

STEP 4
Execute the plan
Let's get an answer

STEP 5
Evaluate the solution
Can this be true?
Competent Problem Solving

1. **Focus** on the Problem

*Translate the words into an image of the situation.*

2. **Describe** the Physics

*Translate the mental image into a physics representation of the problem (e.g., idealized diagram, symbols for knowns and unknowns).*

3. **Plan** a Solution

*Identify an approach to the problem.*

*Relate forces on car to acceleration using Newton's Second Law.*

*Assemble mathematical tools (equations).*

\[
\sum F = ma \\
f_k = \mu N \\
W = mg
\]
3. **Plan a Solution**

*Translate the physics description into a mathematical representation of the problem.*

**Step 1:**

Find \(a_x\):

\[
[1] \quad \sum F_x = ma_x
\]

**Step 2:**

Find \(\sum F_x\):

\[
[2] \quad \sum F_x = T_x - f_k
\]

4. **Execute the Plan**

*Translate the plan into a series of appropriate mathematical actions.*

\[
T_x - f_k = ma_x
\]

\[
T \cos \theta - \mu(W - T \sin \theta) = \frac{W}{g} a_x
\]

\[
g \frac{T}{W} (\cos \theta - \mu \sin \theta) - \mu g = a_x
\]

5. **Evaluate the Solution**

**Outline the mathematical solution steps.**

- Solve [3] for \(T_x\) and put into [2].
- Solve [2] for \(\sum F\) and put into [1].
- Solve [1] for \(a_x\).

**Check units of algebraic solution.**

\[
\frac{\text{[m]}}{\text{s}^2} \quad \frac{\text{[N]}}{\text{[N]}} - \frac{\text{[m]}}{\text{s}^2} = \frac{\text{[m]}}{\text{s}^2} \quad \text{OK}
\]
The problems must be challenging enough so there is a real advantage to using problem solving heuristics.

1. The problem must be complex enough so the best student in the class is not certain how to solve it.

   The problem must be simple enough so that the solution, once arrived at, can be understood and appreciated.
2. The problems must be designed so that

- the major problem solving **heuristics are required** (e.g. physics understood, a situation requiring an external representation);

- there are several **decisions** to make in order to do the problem (e.g. several different quantities that could be calculated to answer the question; several ways to approach the problem);

- the problem **cannot be resolved in a few steps by copying a pattern**.
3. The task problem must connect to each student’s mental processes

- the situation is **real** to the student so other information is connected;
- there is a **reasonable goal** on which to base decision making.
Context-rich Problems

• Each problem is a short story in which the major character is the student. That is, each problem statement uses the personal pronoun "you."

• The problem statement includes a plausible motivation or reason for "you" to calculate something.

• The objects in the problems are real (or can be imagined) -- the idealization process occurs explicitly.

• No pictures or diagrams are given with the problems. Students must visualize the situation by using their own experiences.

• The problem can not be solved in one step by plugging numbers into a formula.
Context-rich Problems

In addition, more difficult context-rich problems can have one or more of the following characteristics:

- The unknown variable is not explicitly specified in the problem statement (e.g., Will this design work?).

- More information may be given in the problem statement than is required to solve the problems, or relevant information may be missing.

- Assumptions may need to be made to solve the problem.

- The problem may require more than one fundamental principle for a solution (e.g., Newton's Laws and the Conservation of Energy).

- The context can be very unfamiliar (i.e., involve the interactions in the nucleus of atoms, quarks, quasars, etc.)
The Dilemma

Start with simple problems to learn expert-like framework.
Success using novice framework.
Why change?

Start with complex problems so novice framework fails
Difficulty using new framework.
Why change?
Why We Use Cooperative Group Problem Solving

1. Using a problem solving framework seems too long and complex for most students.

   Cooperative-group problem solving allows practice until the framework becomes more natural.

2. Complex problems that need a strategy are initially difficult.

   Groups can solve successfully solve them so students see the advantage of a logical problem-solving framework early in the course.
Why We Use Cooperative Group Problem Solving

3. The external group interaction forces individuals to observe the planning and monitoring skills needed to solve problems. (Metacognition)

4. Students practice the language of physics -- "talking physics."

5. Students must deal with and resolve their misconceptions.

6. In whole-class discussions, students are less intimidated
   Their answer or question has been validated by the others.
Cooperative Groups

- Positive Interdependence
- Face-to-Face Interaction
- Individual Accountability
- Explicit Collaborative Skills
- Group Functioning Assessment
Why Group Problem Solving May Not Work

1. Inappropriate Tasks
2. Inappropriate Grading
3. Poor structure and management of Groups

Curricular Elements Do Not Correspond to the Instructor’s Beliefs or Values
EVERYTHING WE WANT STUDENTS TO DO IS GRADED

“If you don’t grade it, they don’t learn it!”

We want students to present a logical, organized problem solving procedure using fundamental physics principles.

• Only basic equations given on test are allowed.
• Small, but significant part of grades is for group problem solving.
• During lecture, in class questions are occasionally collected and graded.
• Prediction solutions for lab problems are graded.

ABSOLUTE SCALE

“If you win, I do NOT lose.”
Structure and Management of Groups

1. What is the "optimal" group size?
   • three (or occasionally four)

2. What should be the gender and performance composition of cooperative groups?
   • two women with one man, or same-gender groups
   • heterogeneous groups:
     - one from top third
     - one from middle third
     one form bottom third
     based on past test performance.
3. How often should the groups be changed?

For most groups:

• stay together long enough to be successful
• enough change so students know that success is due to them, not to a "magic" group.
• about four times first semester, twice second semester
Structure and Management of Groups

4. How can problems of dominance by one student and conflict avoidance within a group be addressed?

- Group problems are part of each test. One common solution that all members sign.
- Assign and rotate roles:
  - Manager
  - Skeptic
  - Checker/Recorder
  - Summarizer
- Most of grade is based on individual problem solving.
- Students discuss how they worked together and how they could be more effective.
5. How can individual accountability be addressed?

- assign and rotate roles, group functioning;
- seat arrangement -- eye-to-eye, knee-to-knee;
- individual students randomly called on to present group results;
- occasionally a group problem counts as a test question -- if group member was absent the week before, he or she cannot take group test;
- each student submits an individual lab report. Each member of the group reports on a different problem.
Appropriate Tasks

The problems must be challenging enough so there is a real advantage to working in a group.

1. The problem must be complex enough so the best student in the group is not certain how to solve it.

   The problem must be simple enough so that the solution, once arrived at, can be understood and appreciated by everyone in the group.
2. The task must be designed so that

- everyone can contribute at the beginning (e.g., a situation difficult to visualize requires an external representation);

- there are several decisions to make in order to do the task (e.g., several different quantities that could be calculated to answer the question; several ways to approach the problem); everyone’s agreement is necessary.

- the task relies on applying a strategy not remembering a pattern
Cart A, which is moving with a constant velocity of 3 m/s, has an inelastic collision with cart B, which is initially at rest as shown in Figure 8.3. After the collision, the carts move together up an inclined plane. Neglecting friction, determine the vertical height $h$ of the carts before they reverse direction.

Figure 8.3
You are helping a friend prepare for the next skateboard exhibition. The plan for the program is to take a running start and then jump onto a heavy duty 8-lb stationary skateboard. Your friend and the skateboard will glide in a straight line along a short, level section of track, then up a sloped concrete wall. The plan is to reach a height of at least 10 feet above the starting point before turning to come back down the slope. The fastest your friend can run to safely jump on the skateboard is 7 feet/second. Knowing that you have taken physics, your friend wants you to determine if the plan can be carried out. When you ask, you find out that your friend’s weight is 130 lbs.
The Course as a System

Use strengths of components acting together

Lectures - 3 x 50 min. each week (150 - 400 students)
Model construction of knowledge
Explicit Storyline
Motivate all concepts
Model problem solving
A single explicit framework
Always start from basic principles

Recitation sections - 1 x 50 min. each week (15 students)
Laboratories - 1 x 110 min. each week
Coach problem solving
Same framework as lecture
Same concepts as lecture
The End

Please visit our website for more information:

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