ENHANCING COGNITIVE DEVELOPMENT THROUGH PHYSICS PROBLEM SOLVING: EXAMPLE OF A THINKING-SKILLS CURRICULUM

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ABSTRACT

Numerous research studies in the last thirty years have highlighted the inadequacy of the traditional introductory physics course. It has been shown that students who leave such courses tend to have incoherent physics knowledge and mediocre problem-solving skills. Moreover, they have difficulties when engaging in higher-level thinking and their understanding of the scientific process improves little. At the George Washington University (GW), we designed a thinking-skills curriculum that trades "breadth for depth" by reducing content while emphasizing skill building. We used parallel conceptual and procedural learning progressions that have been created based on a taxonomy of physics problems being developed by Teodorescu *et al*. (TIPP: Taxonomy of Introductory Physics Problems). Our course emphasizes concept formation in various procedural contexts fostered by different curricular units. This approach allows us to explicitly link physics problems and exercises to the higher-order thinking skills we want students to develop while addressing the common student complaint that the various course elements, such as textbook readings, lecture materials, homework problems and lab exercises, appear disjointed and unrelated to each other. Our framework can be adapted to many curricular settings and can be continuously adjusted throughout the semester. We present our methodology and our preliminary results from the initial phase of testing.

KEYWORDS
Cognitive science, physics education research, curriculum design, problem solving

INTRODUCTION

Over the past several decades the Physics Education Research (PER) community has expended considerable effort assessing the shortcomings of traditional teaching methods to provide students with a deeper understanding of physics principles in a coherent framework. A vast amount of newly developed curricular materials has demonstrated the need for active engagement, student-centered learning environments that emphasize cognitive processing over information gathering. Yet the positive gains in conceptual physics knowledge attained by many of the innovative instructional methodologies have not necessarily translated into improved problem solving, but rather revealed the complex and dynamic nature of the problem-solving process. Why do we as physics educators care so much about problem solving? It is not only because it measures students' ability to apply physics concepts to accomplish an objective, but it also reflects our belief that developing problem-solving competency fosters the higher cognitive skills of critical thinking and quantitative reasoning far beyond any particular physics context. The need to enhance quantitative literacy in the citizenry of the technological society of the 21st century has been pointed out in many recent U.S. national reports. Among the STEM (Science, Technology, Engineering, Mathematics) fields, physics may arguably be the one most suited to develop the thinking skills needed for problem solving.

This paper describes the approach we use at GW to reform our introductory algebra-based physics course and how we monitor the students' progress. Several years ago, we started to redesign our introductory algebra-based curriculum in a manner that addresses contemporary educational requirements. Our physics course focuses on problem solving and it is based on the existing research on physics problem-solving expert-novice behavior (Gerace, 2005; Redish, 2003; Gerace, 2001) and the cognitive science discoveries (Jardine, 2006; Etkina, 2004; Redish, 1994). We aim to help students become more expert-like problem solvers by exposing them to research-based and textbook-based physics problems. These problems are carefully chosen according to a taxonomy of physics problems we are developing (Teodorescu, Bennhold and Feldman, 2007) and implemented according to a new protocol that we have created. This protocol addresses the following guidelines (Mayer, 2003) for the design of successful, domain-specific, problem-solving instruction: "(a) focus on a few well-defined skills, (b) contextualize the skills within appropriate tasks, (c) personalize the skills through social interaction in group settings, and (d) accelerate the learning such that students learn higher-level skills along with lower-level skills". We guide students through the Piagetian phases: *assimilation*, *accommodation* and *equilibration* (Jardine, 2006) using the *New Taxonomy of Educational Objectives* by Marzano (Marzano, 2007). Employing this taxonomy we designed a new problem-solving protocol: GW-ACCESS [Assess the problem, Create the drawing, Conceptualize the strategy, Execute the solution, Scrutinize your results, Sum up your learning]. Our student-centered framework seeks to stimulate intellectual development through several components: 1) engaging students in a variety of tasks that need to be resolved in different contexts, 2) clearly communicating the content, cognitive and epistemological objectives to students, 3) providing efficient feedback in a timely manner, and 4) fostering an instructional atmosphere open to friendly dialogue and deep respect towards students efforts, (Felder and Brent, 2004). Special importance is given to the students' epistemological beliefs and their attitudes towards physics and learning physics (Elby, 2001; Adams, Perkins, Podolefsky, Dubson, Finkelstein and Wieman, 2006). We address such issues explicitly in our course.

GW INTRODUCTORY ALGEBRA–BASED PHYSICS CURRICULUM

The overarching learning objectives of our course relate to the physics content the students learn, the competencies they acquire and the dispositions they hold about science in general and physics in particular:

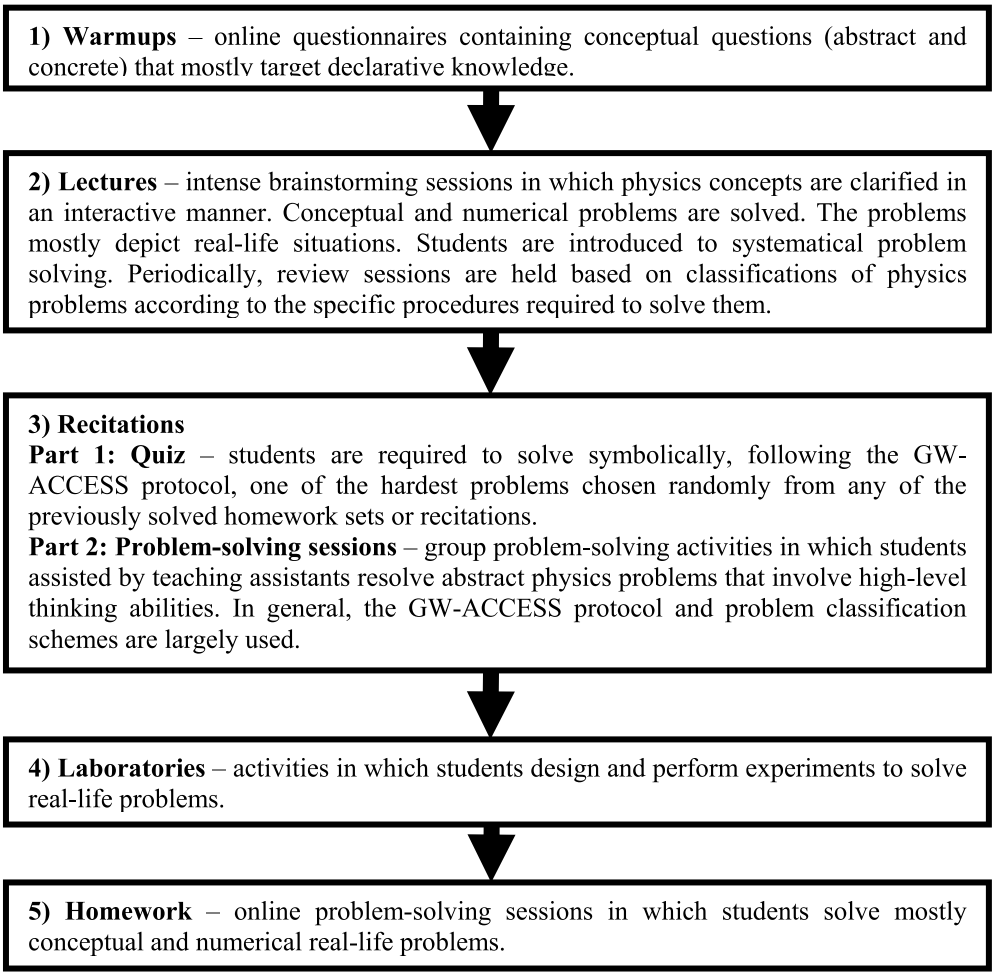
- To convey basic facts, concepts and principles about the laws of nature;
- To help students acquire correct conceptions about how nature works and how science works;
- To enhance student abilities to solve problems, think critically and reason scientifically;
- To raise student confidence levels in their problem-solving abilities;
- To foster each student's innate curiosity about the universe;
- To have students appreciate the real-world connections between the physics classroom and nature.

The activities that students perform are organized in five curricular units:

- *Warmups* - sets of conceptual questions that students need to answer before coming to class. These questions target very basic physics concepts that students should be able to understand after they read the textbook prior to the lecture. Their purpose is to provide the students with the necessary knowledge for the particular lecture. The Warmups are made available to students through an online course management system (LON-CAPA), 24 hours before the lecture.
- *Lectures* - two 75 minute sessions per week that consist of three parts: 1) assessment of students' individual preconceptions about physics, 2) correction of the wrong preconceptions and teaching of the scientific truths, 3) modeling physics problem-solving abilities. The lectures use modern interactive teaching techniques (Mazur, 1997). The classroom is equipped with an electronic student response system (Turning Point).
- *Recitations* - one 90 minute meeting per week during which the students practice problem solving. These activities start with a closed-book quiz based on homework and recitation problems solved previously by the students. The quiz usually requires a symbolical solution. Its purpose is to provide the students with feedback on their ability to solve problems, enabling them to gauge their performance in this course. The quiz also helps students develop the ability to solve symbolical problems. Later in the recitation, students are exposed to cognitively complex physics problems that they solve following the GW-ACCESS problem-solving protocol and classification schemes

that organize the various classes of problems typical for each chapter. The GW-ACCESS protocol and the classification schemes are detailed later in this paper.

- *Laboratories* - one 60 minute session per week in which students work in groups to devise and perform experiments. We follow the ISLE labs model (Investigations Science Learning Environment), (Karelina and Etkina, 2007). During some of these activities, students use Data Studio software from PASCO to acquire and analyze data.
- *Homework* - two weekly sets, each containing 9 problems. The homework problems as well as the Warmups are offered to students through LON-CAPA. This online system provides instant feedback, permits multiple attempts, and offers an electronic bulletin board for discussions.



1) Warmups – online questionnaires containing conceptual questions (abstract and concrete) that mostly target declarative knowledge.

2) Lectures – intense brainstorming sessions in which physics concepts are clarified in an interactive manner. Conceptual and numerical problems are solved. The problems mostly depict real-life situations. Students are introduced to systematical problem solving. Periodically, review sessions are held based on classifications of physics problems according to the specific procedures required to solve them.

3) Recitations
Part 1: Quiz – students are required to solve symbolically, following the GW-ACCESS protocol, one of the hardest problems chosen randomly from any of the previously solved homework sets or recitations.
Part 2: Problem-solving sessions – group problem-solving activities in which students assisted by teaching assistants resolve abstract physics problems that involve high-level thinking abilities. In general, the GW-ACCESS protocol and problem classification schemes are largely used.

4) Laboratories – activities in which students design and perform experiments to solve real-life problems.

5) Homework – online problem-solving sessions in which students solve mostly conceptual and numerical real-life problems.

Figure 1. Distribution of problem-solving activities in the GW introductory algebra-based course.

Figure 1 shows schematically the problem-solving learning cycle that we employ and describes how we balance conceptual vs. numerical and abstract vs. concrete aspects of problem solving across the curriculum units.

MARZANO'S NEW TAXONOMY OF EDUCATIONAL OBJECTIVES

Marzano's New Taxonomy (MNT), released in its final form in 2007 (Marzano, 2007), updates 50 years of learning research from educational psychology and the cognitive and behavioral sciences. It is based on a theory of human thought and is constructed to not only describe phenomena related to the learning and thinking process but also to be able to predict outcomes. Furthermore, it extends the hierarchy of mental processing to include meta-cognitive aspects and thus provides a system that models both the flow of information and the levels of self-awareness of the student. Briefly, the New Taxonomy is a two-dimensional model with six levels of cognitive processing as one dimension and three domains of knowledge as the other dimension. The six levels themselves fall into three distinct categories (Self, Meta-Cognitive, and Cognitive) according to the level of consciousness required to control their execution:

- Level 6: *Self-System*
- Level 5: *Meta-cognitive system*
- Level 4: Knowledge utilization (*Cognitive system*)
- Level 3: Analysis (*Cognitive system*)
- Level 2: Comprehension (*Cognitive system*)
- Level 1: Retrieval (*Cognitive system*)

The highest level (6) denotes the so-called Self-System that contains a network of interrelated beliefs, attitudes and expectations that are involved in making judgments as to whether to engage in a new task. It is at this level that the motivation for accomplishing the goal is determined. If the decision is made to engage in a new task, the Meta-Cognitive System (Level 5) is activated. At this level, goals relative to the new task would be defined and strategies would be developed for reaching those goals. Finally, the Cognitive System (Levels 1-4) is responsible for the effective processing of the information, such as classifying, organizing ideas, making inferences and executing operations.

In MNT, the Self, Meta-Cognitive and Cognitive Systems operate upon the other dimension of the taxonomy, namely, the type of knowledge. Clearly, the success of accomplishing a certain task is highly dependent on the amount and the quality of the necessary knowledge. According to MNT, the knowledge that is specific to any subject area can be organized into three general categories or knowledge domains: *declarative knowledge* (*information), procedural knowledge (mental procedures)* and *psychomotor procedures*, each domain being further subdivided. The domain of *information* is different in both form and function from the domain of *mental procedures*; while the former specifies the "what" of a particular task, the latter refers to the "how" of accomplishing that task. This distinction between content knowledge and process knowledge is considered basic by most educational psychologists and cognitive researchers today. The third knowledge domain of *psychomotor procedures*, essential in areas such as neurosurgery or piloting an airplane, is not considered relevant to solving introductory physics problems and is therefore not included in this project. Table 1 shows schematically how we apply MNT to physics problem solving.

Table 1. Marzano's New Taxonomy, as applied to the cognitive processes needed for physics problem solving. All of the categories listed below apply to the two knowledge domains of *information* and *mental procedures* (The only exception is sublevel 1b – *executing* – which applies only to mental procedures and not to information). Note that for levels 2b, 3a and 4b we have changed the name of the cognitive process, and Marzano's original term appears in parentheses.

Level 1: RETRIEVAL	a) Recalling – producing/recognizing basic physics knowledge related to the problem (but not necessarily understanding the structure of the knowledge). b) Executing – performing a procedure or task needed to solve the physics problem without significant error (but not necessarily understanding how and why the procedure works).
Level 2: COMPREHENSION	a) Integrating – identifying the essential features of the physics knowledge needed for the problem and separating critical from non-critical characteristics.

	b) Representing *(Symbolizing*) – constructing an accurate symbolic image of the physics information or mental procedure needed to solve the physics problem.
Level 3: **ANALYSIS**	a) Ranking (*Matching*) – identifying similarities/differences and relationships between the physics problem components. b) Classifying – identifying super-ordinate and subordinate categories into which the physics knowledge related to the problem can be organized. c) Analyzing Errors – making and checking assumptions and estimates and verifying their reasonableness related to the physics knowledge involved in the problem d) Generalizing – constructing new generalizations or principles from available physics knowledge. e) Specifying – generating new applications or logical consequences from available physics knowledge.
Level 4: **KNOWLEDGE UTILIZATION**	a) Decision Making – selecting between two or more alternatives that initially appear equal (such as different problem-solving or experimental procedures). b) Overcoming Obstacles (*Problem Solving*) – accomplishing a goal or task for which obstacles or limiting conditions exist. c) Experimenting – generating and testing hypotheses for the purpose of understanding phenomena, using rules of evidence that adhere to statistical hypothesis testing. d) Investigating – generating and testing hypotheses about past, present and future events, using well-constructed and logical arguments as evidence.
Level 5: **META-COGNITION**	Specifying goals, process monitoring, monitoring clarity and accuracy
Level 6: **SELF SYSTEM**	Examining importance, efficacy, emotional response and motivation

THE GW-ACCESS PROBLEM-SOLVING PROTOCOL

Most physics problem-solving protocols have their roots in mathematics problem solving or from the field of general problem solving (chess, games, puzzles). One of the pioneers in this area, Polya (1945), developed a four-step general approach for problem solving: *understand the problem, devise a plan, carry out the plan, and look back*, which was later adopted by (Beichner, Saul, Abbott, Morse, Deardorff, Allain, Bonham, Dancy and Risley, 2007) and modified to the GOAL protocol (*Gather information*, *Organize and plan*, perform the *Analysis* and *Learn* from your efforts) used in SCALE-UP. Similar frameworks were used in later research that focused on students becoming better problem solvers. Reif, Larkin and Brackett (1976) used the following approach: *description*, *planning*, *implementation* and *checking* for research purposes — Schoenfeld (1978) created a similar one for teaching purposes. Wright and Williams (1986) designed the *WISE* procedure: *What's happening* (Identify givens and unknown, draw a diagram, identify the relevant physics principle), *Isolate the unknown* (select an equation, solve algebraically, look for additional equations if one is insufficient), *Substitute* (plug in both numbers and units), and *Evaluate* (check the reasonableness of the answer). Heller and Heller (1995) developed a five-step framework: *Focus the problem*, *describe the physics*, *plan the solution*, *execute the plan* and *evaluate the answer*. In contrast to the protocols discussed above that are based on heuristics, we developed a protocol that maps to the latest educational research and relates to a framework of cognitive processes and a model of behavior (Marzano, 2007):

A – Assess the problem (Classifying/matching information and mental procedures – levels 3a, 3b)
Cognitive science research has shown (Chi, Feltovici and Glaser, 1981) that experts begin the problem-solving process by identifying the general category to which the problem belongs. Physicists first identify the general area of physics pertaining to the problem (mechanics, optics, heat, etc.), then further specify one or more subcategories (energy conservation, rotational motion, etc.). Experts are able to perform such classification and ranking because their physics-specific knowledge is strongly interconnected and hierarchically structured. For novices, such structures must be explicitly developed.

C – Create a drawing (Representing/symbolizing information – level 2b)
Experts are able to create and translate between multiple representations of the information, with the standard representations in physics being diagrams, words, equations, plots, and tables of numbers. Faced with a word problem, experts will usually draw a diagram that represents the available information. Marzano refers to the process of translating between knowledge representations as *Symbolizing*, we employ the more commonly used term *Representing*.

C – Conceptualize the strategy (Integrating, generalizing, specifying, decision making, overcoming obstacles – levels 2a, 3d, 3e, 4a, 4b)
Unless a solution is obvious to them, experts will formulate a forward-looking concept-based strategy to solve a problem. Many higher cognitive processes can be involved in this step; it is therefore found to be the most difficult thinking skill to develop for most students. For an expert, this is the crucial step of the problem-solving process: separating critical from non-critical components of the information provided, generalizing from existing physics knowledge, specifying new applications, making decisions between alternative procedures and identifying obstacles when limiting conditions exist.

E – Execute the solution (Executing mental procedures – level 1b)
This is the step that novice students usually begin with when solving physics problems: "What is the right equation I need to use in order to plug in the numbers and get my result?" According to Marzano's taxonomy, this is a lower-level thinking skill that only requires how to execute an algorithm or a procedure without the deeper understanding of what it means to perform this procedure. Novices will tend to get stuck at this stage when their selected algorithm does not lead to the solution of the problem.

S – Scrutinize your results (Analyzing errors of information and mental procedures – level 3c)
Experts will perform a qualitative analysis of their result to verify that the answer is reasonable. This involves checking reasonable assumptions related to the physics information, making estimates and looking for errors. This is a higher-level thinking skill referred to as Analyzing Errors by Marzano.

S – Sum up your learning (Meta-learning – level 5)
Finally, experts reflect on their own problem-solving ability, and identify their strengths and weaknesses. This form of meta-cognitive processing is present not only at the end, but to some degree during the entire problem-solving process; it involves self-monitoring of efficacy, efficiency, clarity and accuracy by the expert. Novices usually suffer cognitive overload and have already expended all of their mental resources on the problem-solving process. Thus, meta-cognitive reflection during the problem-solving process usually develops slowly and needs to be explicitly encouraged and nurtured.

Note that at this stage we do not include "lab problems" that would involve experimentation and investigation (levels 4c and 4d). The relationship between the ACCESS protocol and the cognitive processes from Marzano's taxonomy is summarized in Table 2. Table 3 outlines the learning progression used to teach the ACCESS component processes in parallel to the physics content in a particular week. As the first step we have only included the process *Integrating* (level 2a) in the strategy component of the protocol. Students will not work with the complete protocol until halfway through the semester. The problems and exercises used in the course are matched with the cognitive process that is targeted for development using a taxonomy of physics problems (TIPP) that we have developed (Teodorescu, Bennhold, Feldman, 2007). For example, the particular component skill of *Representing* for the knowledge domain of *Information* can be fostered and practiced by the wide range of knowledge representation exercises that have been developed extensively by the PER community over the last 30 years (Kohl, Rosengrant and Finkelstein, 2006; Rosengrant, Etkina and van Heuvelen, 2006; van Heuvelen and Etkina, 2006; Redish, 2003; Dufresne, Gerace and Leonard, 1997). Other examples are the so-called Ranking Tasks (O'Kuma, Maloney and Hieggelke, 2000) which develop the skill of *Ranking*, and the so-called Unreasonable-Results problems (Urone, 1998) which relate to the skill of *Analyzing Errors*. With the help of TIPP, we identified classes of problems that are necessary for a stage of cognitive development but do not exist in the PER literature, *e.g.*, problems that involve *Classification* of *Information* and *Mental Procedures*. In such cases, we created new exercises.

Table 2. The link between the ACCESS protocol and cognitive processes from Marzano's taxonomy.

ACCESS	Cognitive processes involved
Assess the problem	*Classifying, Ranking (Level 3a, 3b)* – Classify the problem.
Create a drawing	*Representing information (Level 2b)* – Create representations of the information and translate between them in the problem solving process.
Conceptualize the strategy	*Integrating, generalizing, specifying, decision making, overcoming obstacles (Levels 2a, 3d, 3e, 4a, 4b)* – Formulate forward-looking, concept-based strategy.
Execute the solution	*Executing mental procedures (Level 1b)* – Execute the algorithm or procedure (Typical first step for novices - What equation do I use?).
Scrutinize your results	*Analyzing errors, checking reasonableness (Level 3c)* – Perform qualitative analysis to determine if answer is reasonable, check assumptions and make estimates.
Sum up your learning	*Meta-learning (Level 5)* – Reflect on problem solving process, identify strengths and weaknesses.

Table 3. The first semester of the GW algebra-based introductory physics sequence (Fall 08) using only Level 2a for *Conceptualize the strategy*.

Wee	Physics Content	Cognitive Process (Thinking Skill)	
		Information	Mental Procedures
1	Introduction – What is Physics?	Introduction – What is a Thinking	
1	Forces, Vectors	Integrating (2a)	Executing (1b)
2	Newton's Laws	Representing	Integrating (2a)
3	A special case of motion:	Ranking (3a)	Integrating (2a)
4	A special case of motion:	Classifying (3b)	Ranking (3a)
5	*Review and Midterm 1*	*Review and Midterm 1*	
6	Energy Conservation	Analyzing errors	Classifying (3b)
7	Collisions and Momentum	Analyzing errors	Analyzing errors
8	Rotational Motion	Using ACCESS and Representing	
9	Fluids: Buoyancy and Fluid	Using ACCESS and Matching	
10	*Review and Midterm 2*	*Review and Midterm 2*	
11	Oscillations	Using ACCESS and Classifying	
12	Waves/Sound	Using ACCESS and Analyzing errors	
13	Tying it all together	Using ACCESS	
14	Tying it all together	Using ACCESS	
Fina	*Cumulative Final Exam*	*Cumulative Final Exam*	

We combine traditional and research-based physics problems such that, during each week, as students learn a new topic, they are also gradually exposed to a new type of thinking that involves certain cognitive processes. The processes targeted are: filtering the relevant information, creating a strategy, problem classification, ranking of different physical quantities, comparison and analysis of different phenomena, analyzing procedural errors (*i.e.* identify errors in wrong solutions offered) or informational errors (*i.e.* numbers, premises). Figure 2 shows an example in which students exercise processes like creating a strategy, ranking of information and error analysis of information. We used this learning progression within the recitation session.

Week 6 ***Physics Topic: Energy*** ***Cognitive Process: Error Analysis/Estimating (level 3c)***

Problem: The efficiency of a system is defined by Eff = P_{out}/P_{in}, where P_{in} is the power consumption or input, and P_{out} is the power output going into useful work or the desired form of energy. A car advertisement claims that its 900 kg car accelerated from rest to 60 m/s and drove 100 km, gaining 5 km in altitude by going up the mountains, on 1 gallon of gasoline. The average force of friction due to air resistance was 1700 N. Calculate the car's efficiency, knowing that a gallon of gasoline provides 1.3×10^8 J. What is unreasonable about the result, or which premises are inconsistent? (Urone, 1998)

Week 4 ***Physics Topic: Kinematics*** ***Cognitive Process: Ranking/Matching (level 3a)***

Problem: 1) What is the distance traveled in x-direction by a projectile launched at an angle of *30°* with initial velocity *10 m/s,* from the ground? 2) Find how long it takes a vertically launched body from the ground with initial velocity *4m/s* to reach its maximum height. What is the maximum height? 3) Find the velocity and the position of an object dropped vertically from *10m* above the ground, *2s* after release.

Establish similarities and differences between the above motions by completing the following sentences:

The acceleration of the object for motions 1), 2) and 3), (neglecting air resistance), always points (downwards, upwards)........... and always has magnitude equal to ....

For motions 1) and 2), when the object reaches its maximum height, the vertical component of the velocity is ....

Week 2 ***Physics Topic: Newton's 2nd law*** ***Cognitive Process: Writing a strategy/Integrating information and mental procedures (level 2a)***

Problem: Write a strategy for the following problem: Two blocks are connected by a light-weight, flexible cord that passes over a frictionless pulley. If the masses of the blocks are *m* and *M*, find the accelerations of the two blocks and the tension

Figure 2. An example of a learning progression taken from the recitation. Note how the cognitiveprocesses targeted increase in complexity as more content is learned from week 2 to week 6.

METHODOLOGY USED TO ENHANCE THE COHERENCE OF KNOWLEDGE

For each chapter we created classifications of physics problems according to the physics laws or concepts that are required to solve them. As an example, Figure 3 shows the scheme we use for the unit on fluids. Students use these charts when they solve problems during recitations and homework. The charts have multiple pedagogical functions: a) to implicitly trigger students' focus towards the deep features of the physics problem and a procedure-oriented thinking; b) to help initiate the problem-solving process by making the activation of knowledge easier; c) to help students build locally coherent entities of knowledge; d) to raise students' level of motivation by explicitly showing them that problems with vastly different surface features can nevertheless employ the same physics concepts. We hold regular review sessions where students are taught to acquire the "big picture" of the material using more complex concept maps that link the chapters' knowledge.

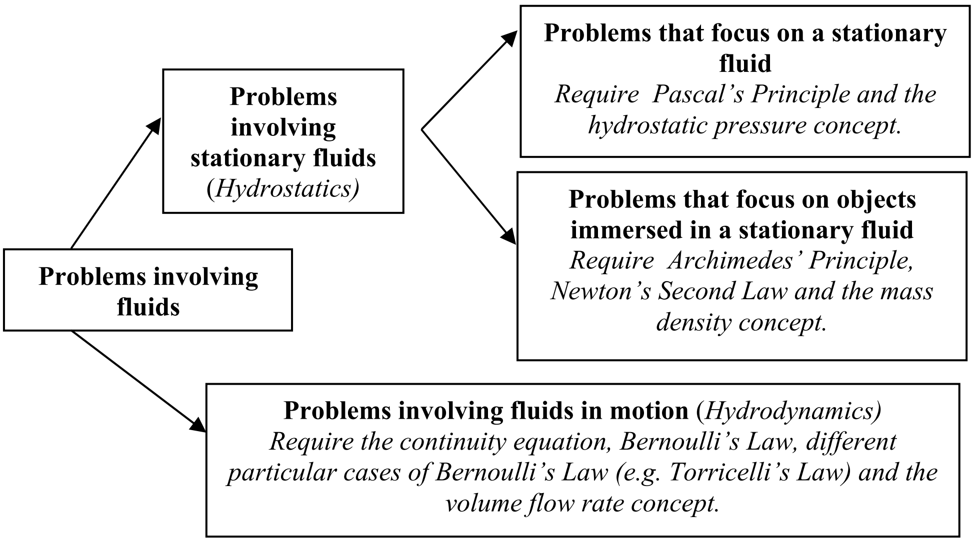


Figure 3. Problem classification scheme used for the unit on fluids.

ASSESSMENT OF STUDENT PERFORMANCE

Rubrics are a common tool to provide formative assessment of student performance. As scoring devices that include descriptions of different levels of accomplishment, rubrics are associated with numerical scores, with the highest level reflecting perfect completion of a task or total proficiency in the area being evaluated (Brookhart, 1999). For the purpose of this project, we have chosen rubrics as a straightforward method of measuring the improvement of student performance in component skills as applied to solving a physics problem, independent of their performance in other parts of the problem-solving process. For example, rubrics allow us to score a student's free-body diagram regardless of whether the student obtained the correct answer to the entire problem. Thus, rubrics reveal not only which skills students have learned, but also which skills actually increase the students' ability to solve the entire physics problem correctly. In our implementation of rubrics, we follow the model of (Etkina, van Heuvelen, White-Brahmia, Brookes, Gentile, Murthy, Rosengrant and Warren, 2006).

Table 4 shows an example of a preliminary rubric for the classification component skill needed for the first step of the ACCESS protocol. This rubric was developed and tested at GW in our Fall 2007 Phys 11 course with 121 students. Several physics undergraduate and graduate students participated in the rubric validation, leading to an average inter-rater reliability of 0.8. As a pre- and post-test, the students had to classify 8 mechanics problems, for a maximum total of 24 points. The pre-test was given in the third week of the semester; the post-test was part of the final exam. Figure 4a compares the pre/post test scores while Figure 4b shows the absolute gain, defined as gain = post − pre (scores). Student performance improved significantly during the course of the semester with an average gain of 5.07.

This rubric will be refined during the upcoming semester and similar rubrics will be developed for the other component skills.

As we have begun experimenting with various parts of our thinking-skills curriculum in our traditional lecture class setting, we have administered the CLASS to our algebra-based course at GW (called Phys 1 at that time) in Spring 2007 and Fall 2007. The results are shown in Figure 5 for the normalized gain in the eight categories specified in (Adams, Perkins, Podolefsky, Dubson, Finkelstein and Wieman, 2006) for a typical calculus-based course. Overall, our results indicate a generally positive trend, especially for Spring 2007 (gray bars), compared to the negative trend reported in the literature. We point out that this negative trend for typical traditional instruction is especially striking for the three categories related to problem solving. This reinforces the need to not only raise students' competency in problem solving but also to address their confidence level and the beliefs they hold about scientific problem solving.

The Force Concept Inventory assessment (Hestenes and Halloun, 1995; Hestenes, Wells and Swackhamer, 1992) was also administered pre and post instruction, leading to an average normalized gain of 0.35±0.02.

Table 4. Classification rubric.

Component Skill	**Missing (0)**	**Inadequate (1)**	**Needs some improvement (2)**	**Adequate (3)**
Is able to classify the problem according to the underlying physics concepts and/or laws	No attempt is made to classify the problem.	The problem is classified incorrectly or according to surface features.	The problem is classified correctly but too generally (physics principles not included).	The problem is classified according to correct physics concepts and/or laws.

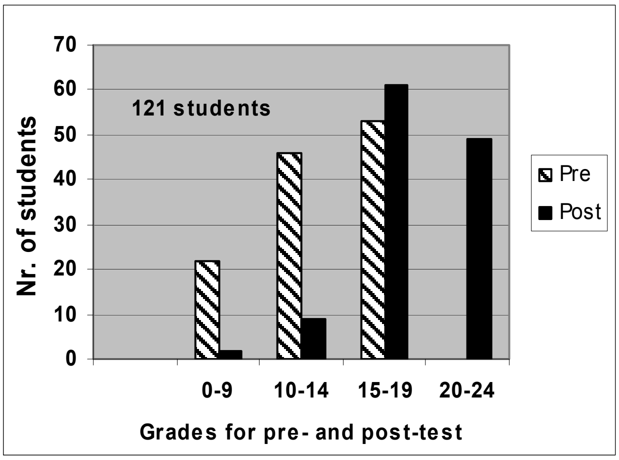


Figure 4a: Pre/post test scores for the classification pre-/post-test, consisting of 8 classification tasks. Note that the mean shifted towards the higher scores.

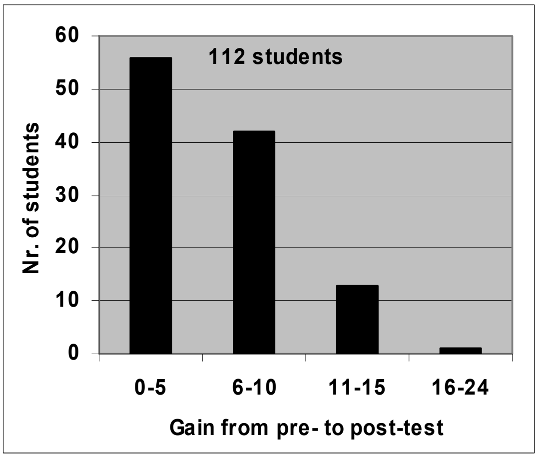


Figure 4b: Student scores for the absolute gain = post – pre for the same classification pre-/post-test.

CONCLUSIONS

We have presented in this paper the underlying methodology we are developing to teach physics problem solving in our introductory physics course. This methodology aims to put into practice the latest discoveries from educational psychology, cognitive science and physics education research. Besides addressing a deeper conceptual understanding, our framework emphasizes cognitive development and improvement of student attitudes towards science. The instructional environment that we are designing allows for explicit monitoring, control and measurement of the cognitive processes exercised during the instruction period. It is easily adaptable to any kind of curriculum and can be readily adjusted throughout the semester. Preliminary results are encouraging, showing significant progress in all the areas targeted. As we continue to refine our course, more assessments will be administered to better ascertain the efficacy of this pedagogy.

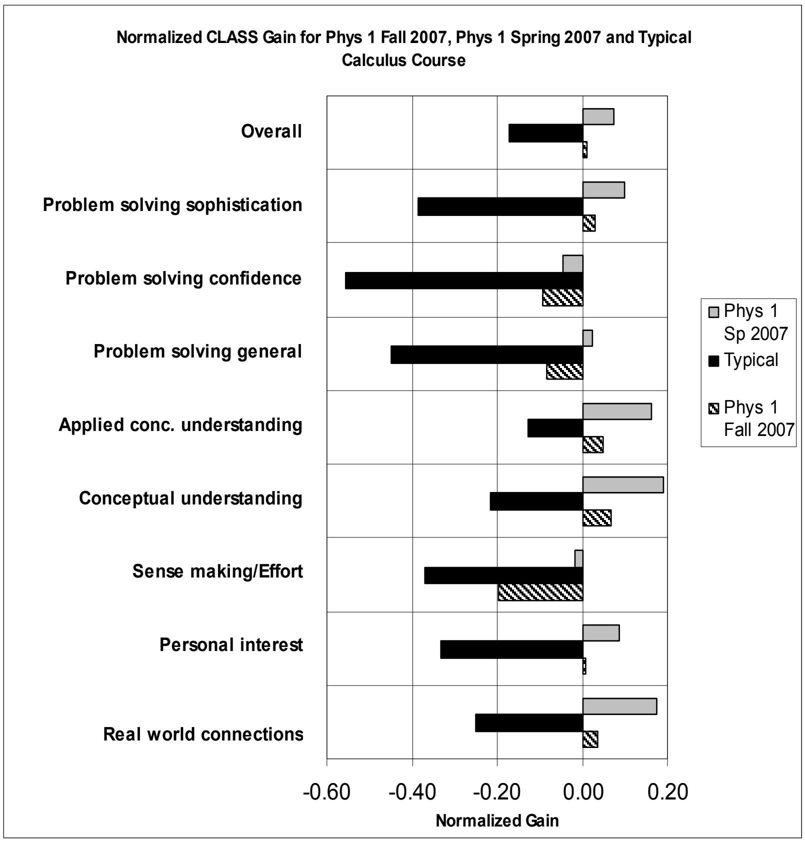


Figure 5. Normalized gain = (post–pre)/ (100–pre) for the CLASS given in two semesters at GW, compared to a typical calculus-based course cited in (Adams, Perkins, Podolefsky, Dubson, Finkelstein and Wieman, 2006).

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