

Curricular Reforms that Improve Students' Attitudes and Problem-Solving Performance

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Abstract

We present the most recent steps undertaken to reform the introductory algebra-based course at The George Washington University. The reform sought to help students improve their problem-solving performance. Our pedagogy relies on didactic constructs such as the *GW-ACCESS problem-solving protocol*, *instructional sequences* and *problem classification schemes* that we have developed and implemented in our introductory physics course. These tools were designed to help advance students in two specific ways: 1) to improve their problem-solving performance and 2) to improve their attitudes towards learning physics. We organized traditional and research-based physics problems such that students experienced a gradual increase in complexity related to problem context, problem features and cognitive processes needed to solve the problem. The instructional environment that we created is easily adaptable to any kind of curriculum and can be readily adjusted throughout the semester. To assess the students' problem-solving performance, we created rubrics that assess key steps of physics problem solving. The Colorado Learning Attitudes about Science Survey (CLASS) was administered pre- and post-instruction to determine students' shift in dispositions towards learning physics. The results show improvements in students' problem-solving performance and in their attitudes towards learning physics.

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Introduction

Numerous research studies in the last 30 years have highlighted the inadequacy of traditional physics courses. Such courses are typically content-oriented and put little emphasis on cognitive processing. It has been shown that students who leave such courses tend to have incoherent physics knowledge and mediocre problem-solving abilities. Moreover, they have difficulties when engaged in high-level thinking, and they show little improvement in their attitudes towards science. Several reports (Czujko, 1997; NRC, 1996; AAAS, 1993) called explicitly or implicitly for reforming the instruction by exposing students to more process-oriented tasks that develop critical thinking and problem-solving abilities that are typically required at their future workplaces.

In recent years, a number of education research groups (Redish & Hammer, 2009; Beichner, Saul, Abbott, Morse, Deardorff, Allain, Bonham, Dancy, & Risley, 2007; Etkina & Van Heuvelen, 2007; McKagan, Perkins, & Wieman, 2006; Novak, Patterson, Gavrin, & Wolfgang, 1999; McDermott & The Physics Education Group of the University of Washington, 1996; Crouch, Watkins, Fagen, & Mazur, 2007) have made sustained efforts to redesign the introductory physics courses in their departments. Their modifications focus on promoting conceptual understanding and higher-level thinking with the instruction.

Prior to 2006, the GW algebra-based physics course (called Phys 11) had evolved from a traditional course to one that implemented technologically advanced methods, such as an electronic student response system coupled with Peer Instruction philosophy, the adoption of an individualized web-based homework system (LON-CAPA, www.loncapa.org), computers in labs with data-acquisition software (PASCO Data Studio) and a special Physics Help Room equipped with terminals and staffed with physics majors, teaching assistants and course instructors to assist students in collaborative problem solving.

With the existing infrastructure for the course already in place, we initiated an effort in 2006 to refocus the curriculum towards problem solving. This reform was motivated by the unsatisfactory problem-solving performance of the students as reported by faculty, by the difficulties in embracing deep-thinking activities as frequently expressed in the course evaluations, and by marginal achievements with existing physics education research instructional strategies. Our efforts were informed by:

- research on physics problem-solving expert-novice behavior (Maloney, 1994; Gerace & Beatty, 2005; Gerace, 2001)
- cognitive science studies (Redish, 2003; Redish, 1994)
- findings about students' epistemological beliefs and their attitudes towards physics and learning physics (Adams, Perkins, Podolefsky, Dubson, Finkelstein, & Wieman, 2006; Elby, 2001)
- educational psychology tools (Marzano & Kendall, 2007; Van Heuvelen, 1991)
- skills and abilities required by employers of future graduates (NACE, 2008).

Among existing research-based reformed courses, the GW curriculum is distinguished by the following characteristics:

- It uses the New Taxonomy of Educational Objectives (NTEO) (Marzano & Kendall, 2007) as a framework for teaching methodologies.
- It is focused more on the design of the course structure rather than on creating new materials.
- It seeks to combine existing research-based materials in a manner that fosters the development of critical thinking in different contexts.
- It utilizes a multi-dimensional assessment.
- It is easily adaptable to any kind of teaching environment.

The GW Course Reform Procedure

Our initial attempts to reform the course sought to answer the following questions:

- 1) *What are the cognitive processes suitable for practice in this type of course at our university?*
- 2) *Which processes need to be explicitly taught and which ones need only to be practiced?*
- 3) *Where and how do the cognitive abilities need to be implemented within the curriculum to produce measurable effects in students' performance?*
- 4) *What training should be provided for Teaching Assistants?*

To answer these questions, during the Spring 2007 semester we introduced about 60 research-based problems (problems that have been developed by physics education researchers) in the recitations and about 200 such problems in the homework. These problems were previously selected to trigger cognitive processes from all levels of NTEO. Professors' observations from lectures were combined with Teaching Assistants' observations from recitations, laboratories and Help Room sessions on a weekly basis. All consistent remarks were retained. In the end, the process of tailoring the course was based on:

- students' performance in warmups (Novak, Patterson, Gavrin, & Wolfgang, 1999), conceptests (Mazur, 1997), quizzes, recitations, homework and exams,
- students' behavior (comments, successes, difficulties) while solving recitation problems and homework problems,
- students' postings on the online discussion board in LON-CAPA,
- students' detailed comments about the curriculum materials and teaching methods in the mid- and end-semester evaluations,
- professors' and Teaching Assistants' collective observations regarding students' behavior.

Taken together, these observations led to three main conclusions regarding instruction:

- Referring to the NTEO, a realistic instructional goal for our class is practicing cognitive processes up to generalization of information and mental procedures.
- All processes need to be made explicit to students while they solve the specific problems.
- A gradual implementation of the different types of thinking seemed appropriate for our environment.

With these observations in mind, we followed the timeline given in Table 1 to reform our course.

Table 1. *The steps followed in reforming the GW algebra-based physics course.*

<i>Semester</i>	<i>Activity</i>
Fall 2006 + Spring 2007	Development of new homework sets and problem-solving recitations
Summer 2007	Development of a new laboratory manual and refining homework and recitations
Fall 2007	Preliminary assessment of homework sets, recitations and lab activities
Spring 2008 + Fall 2008	Adjustment of lectures + Assessment

An important goal was to spend most of the time on the specific design rather than on creating new teaching materials. We aimed to find an instructional approach in which we could make use of the already-existing traditional and research-based materials. For this reason, the term “development” from Table 1 does not refer to creation of new tasks. Rather, it reflects our efforts to design the framework, search for suitable activities among existing teaching materials, implement them, and make adjustments to build a coherent teaching environment.

The GW Course Curriculum Units

The overarching learning objectives of our course relate to the physics content the students learn, the competencies they acquire, and their dispositions about science in general and physics in particular: we aim to help students improve their problem-solving performance and enhance their attitudes towards learning physics. The activities that students perform are organized into five curricular units, as shown in Figure 1:

- *Warmups* – sets of reading quizzes 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 LON-CAPA (www.loncapa.org) 24 hours before the lecture. This online system provides instant feedback, permits multiple attempts, and offers an electronic bulletin board for discussions.
- *Lectures* – two 75-minute sessions per week that consist of three distinct components: 1) assessment of students’ individual preconceptions with Peer Instruction techniques (Mazur, 1997), 2) clarification of the wrong preconceptions, and 3) problem solving. The classroom is equipped with an electronic student response system (*Turning Point*). The final lectures focus on explaining to students why we focused on developing thinking skills, and where and how they can use the abilities they acquired in the future.
- *Recitations* – one 90-minute meeting per week during which the students practice problem solving. The recitation sessions begin with a closed-book quiz based on problems taken from the homework and previous recitation problems. The quiz usually requires a symbolic solution. Its purpose is to provide students with feedback on their ability to solve problems, enabling them to gauge their performance in the course. The quiz also helps students develop the ability to solve symbolic problems. Later in the recitation, students are given 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.
- *Homework* – two weekly sets, each containing 8-10 problems. The homework problems as well as the warmups are offered to students through LON-CAPA.
- *Laboratories* – one 60-minute session per week in which students work in groups to devise and perform experiments. During each lab, students solve a real-world problem (taken or adapted from Heller & Hollabaugh, 1992). We follow the ISLE (Investigative Science Learning Environment) labs model (Etkina & Van Heuvelen, 2007). Table 2 shows the abilities development targeted in parallel with the specific physics topic on a

weekly basis. During some of these activities, students use Data Studio, a software package from PASCO, to acquire and analyze data.

The required textbook for the class was Giambattista, Richardson, & Richardson, 2005. The problems used, besides the required textbook, were selected or adapted from a variety of textbooks and research-based collections (Mazur, 1997; Cutnell & Johnson, 2006; Serway, Faughn, Bennett, & Vuille, 2005; Giancoli, 2005; Urone, 1998; Walker, 2004; O’Kuma, Maloney, & Hieggelke, 2000; Van Heuvelen & Etkina, 2006; McDermott, Shaffer, & University of Washington Physics Education Group, 2002).

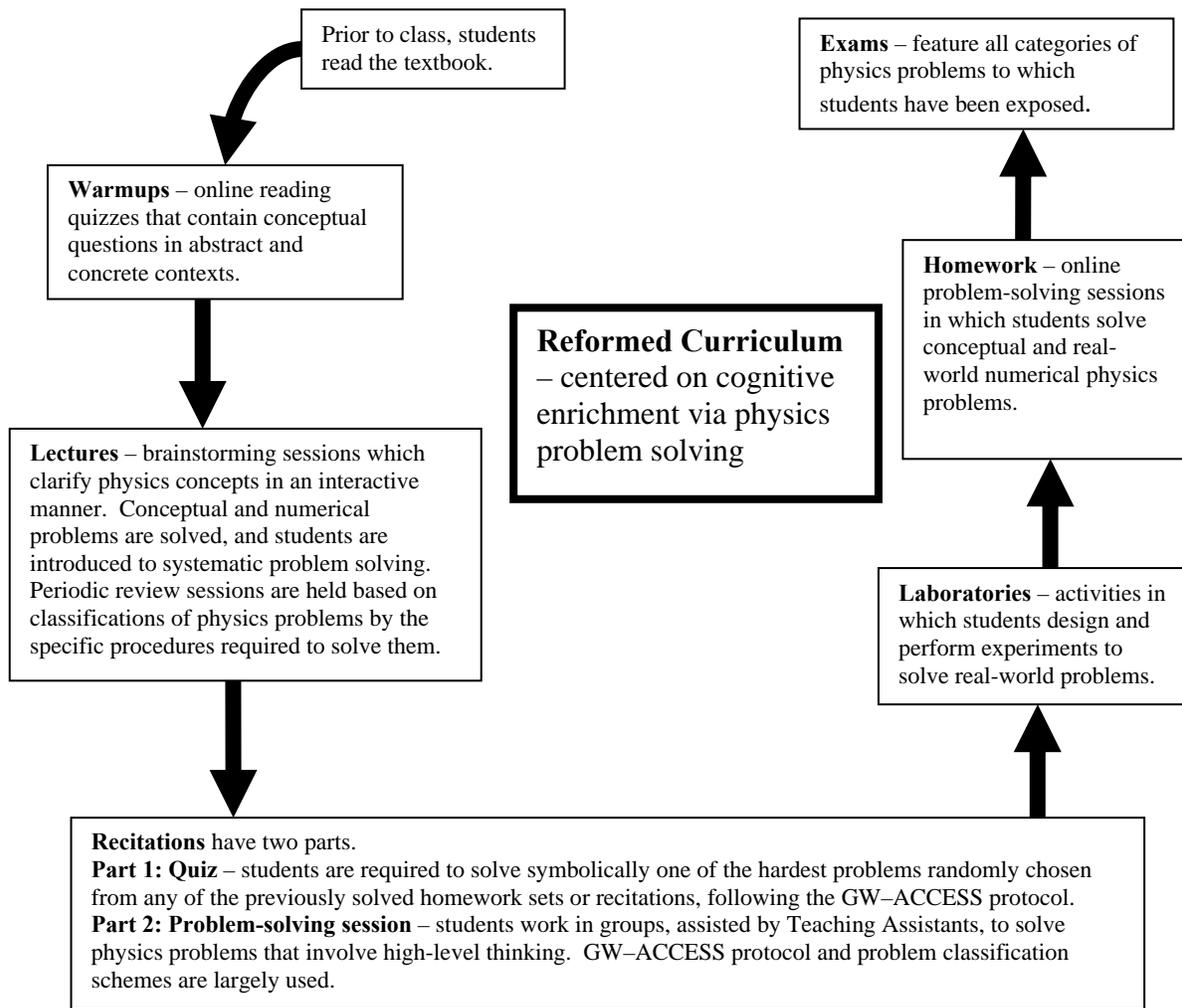


Figure 1. The problem-solving learning cycle employed in the GW algebra-based physics course.

Table 2. The laboratory objectives related to content, abilities and cognitive processes.

<i>Week</i>	<i>Physics Topics</i>	<i>Abilities Targeted</i>	<i>Type of experiment according to ISLE labs classification (Etkina & Van Heuvelen, 2007)</i>	<i>Cognitive processes involved according to the NTEO (Marzano & Kendall, 2007)</i>
1	Lab 1: Tutorial on precision and significant figures. Estimating and measuring time and distance.	Making and recording measurements correctly. Evaluating the precision and accuracy of an instrument	No specific lab type	Retrieval
2	Lab 2: Vectors and Forces	Testing two given hypotheses and eliminating the wrong one.	Testing experiment	Retrieval Comprehension Analysis
3	Lab 3a: Newton's Second Law and Kinematics	Learning data acquisition with Data Studio software. Analyze kinematics graphs.	Testing experiment	Retrieval Comprehension Analysis
4	Lab 3b: Newton's Second Law and Kinematics continued	Learning the meaning of "verifying a relationship".	Testing experiment	Retrieval Comprehension Analysis
5	Lab 4: Circular motion	Learning how to derive mathematical relationships – when you have to derive the quantity you want from what you can actually measure.	Testing experiment	Retrieval Comprehension Analysis Knowledge utilization
6	Lab 5: Linear momentum	Predicting and testing hypothesizes.	Observational experiment	Retrieval Comprehension Analysis Knowledge utilization
7	Lab 6a: Fluids	Designing two experimental methods to measure the same quantity.	Application experiment	Retrieval Comprehension Analysis Knowledge utilization
8	Lab 6b: Fluids continued	Comparing two experimental methods. Learn to evaluate them based on errors minimization.	Application experiment	Retrieval Comprehension Analysis Knowledge utilization
9	Lab 7a: Oscillations and waves	Performing a complete investigation.	Application experiment	Retrieval Comprehension Analysis Knowledge utilization
10	Lab 7b: Oscillations and waves continued	Writing a lab report.	Application experiment	Retrieval Comprehension Analysis Knowledge utilization

The GW Course Methodology

In our view, introductory physics is seen as a “thinking-skills” program, and solving physics problems is a vehicle to promote cognitive growth and development that is intended to transfer to other areas. In a careful review of successful and unsuccessful thinking-skills programs, Mayer (1997) has proposed four issues as guidelines for thinking-skills courses:

- 1) what to teach (*e.g.*, problem solving as a single competency or a collection of component skills),
- 2) how to teach (*e.g.*, focusing on the product or process),
- 3) where to teach (*e.g.*, in a general, domain-independent course or a domain-specific course such as physics),
- 4) when to teach (*e.g.*, after a set of basic skills has been mastered or before).

Mayer and Wittrock (2006) found that thinking-skills courses are most effective under the following conditions:

- 1) The curriculum focuses on one or more component skills that are developed separately, rather than treating problem solving and critical thinking as a single ability that the course tries to improve in general.
- 2) The instructional methods focus on the problem-solving process itself, rather than on obtaining the right answer.
- 3) The students learn and apply the skills within a specific domain, rather than across domains.
- 4) Higher-level skills are developed and practiced even before students have automated the underlying basic skills.

Our methodology is based on NTEO and on the Taxonomy of Introductory Physics Problems (TIPP) (Teodorescu, Bennhold, Feldman, & Medsker, 2013) that we developed for the purpose of this project. The taxonomy that we created establishes a relationship between physics problems and the cognitive processes that they trigger during the solving process. To help students perform better on problem solving, we developed three instructional strategies: *GW-ACCESS protocol*, *instructional sequences*, and *classification*. We used NTEO to establish the cognitive processes we want to exercise in the course and we used TIPP to select the specific physics problems that trigger these processes. The remaining part of this section will detail the theoretical basis, development and implementation of our teaching strategies.

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 and his colleagues (2007) and modified to become their GOAL protocol (*Gather information*, *Organize and plan*, perform the *Analysis* and *Learn* from your efforts) used in SCALE-UP (Beichner, Saul, Abbott, Morse, Dearthoff, Allain, Bonham, Dancy, & Risley, 2007). Similar frameworks were used in later research that focused on students becoming better problem solvers. Reif and his colleagues (1976) used the following approach: *description*, *planning*,

implementation and checking for research purposes; Schoenfeld (1979) 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*.

The protocols discussed above that are based on heuristics have long been recognized as standard approaches to systematic problem solving. The *GW-ACCESS* protocol builds on them, but incorporates our classroom experience into such schemes. While experimenting with these schemes throughout the years, we found that our students did not accept them naturally, often thought that they did not enhance their problem-solving ability, and frequently perceived them as obstacles rather than problem-solving aids. Moreover, they used them in an ineffective way. For instance, for steps like “Description” or “What’s happening” our students would just repeat parts of the problem statement showing no evidence that they can identify the key aspects particular to that problem. Such issues made us conclude that special attention should be paid to how we teach a protocol. The *GW-ACCESS* protocol has many features similar to other protocols, but it is accompanied by its own teaching methodology and assessment. To develop it, we first selected an appropriate taxonomy (NTEO) that organizes the component processes of problem solving. Then, we used expert-novice studies (Maloney, 1994; Gerace & Beatty, 2005; Gerace, 2001) to document the requirements and the implementation of each step. Table 3 shows the *GW-ACCESS* steps and the corresponding cognitive processes from NTEO.

Table 3. *The link between GW-ACCESS steps and NTEO.*

ACCESS stage	Matching cognitive process in NTEO
Assess the problem	Categorization
Create a drawing	Symbolizing
Conceptualize the strategy	Integrating
Execute the solution	Executing
Scrutinize your results	Analyzing errors
Sum up your learning	Meta-cognition

Following this further, we explain in detail the relationship between the *GW-ACCESS* steps and how they link with the NTEO and with expert-novice research (refer to Appendix A).

A – Assess the problem

Cognitive science research has shown (Chi, Feltovici & 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, etc.), then further specify one or more subcategories (energy conservation, momentum

conservation, etc.). Experts can perform such categorizations because their physics-specific knowledge is strongly interconnected and structured. For novices, such structures must be explicitly developed over time.

C – Create a drawing

Experts are able to create multiple representations of the information and translate between those representations in the problem-solving process, with the standard representations in physics being diagrams, words, equations, plots, tables of numbers, etc. Faced with a word problem, experts will usually draw a diagram that represents the available information and then proceed to develop a strategy that identifies the equations needed to solve the problem. In the NTEO, the process of developing and translating between knowledge representations is called *symbolizing*.

C – Conceptualize the strategy

Unless a solution is obvious to them, experts tend to formulate a strategy to solve a problem. Part of formulating the strategy is to separate the critical from the non-critical components of the information provided, and to select the appropriate algorithms needed to proceed towards a solution. In the NTEO, this process of selecting and identifying the relevant information and mental procedures is called *integrating*.

E – Execute the solution

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 the NTEO, *executing* is a lower-level thinking process that only involves performing algorithms or procedures and does not necessarily involve the understanding of what it means to perform these procedures. 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

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 ability referred to as *analyzing errors* in the NTEO.

S – Sum up your learning

Finally, experts reflect on their own problem-solving process and 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, 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.

To address each step of the ACCESS protocol, students have been provided with specific questions accompanied by succinct instructions. Appendix A shows a version of the protocol that we tested in the classroom. This scheme is iterated and enhanced as we probe students’ understanding of the language used to describe each step.

To gradually implement the *GW-ACCESS* plan in the curriculum, we used a complex syllabus (shown in Figure 2) that outlines both the physics content and the highest cognitive process that is to be developed and practiced in a particular week. Here, we refer to the hierarchy of cognitive processes presented in the NTEO – the reader should understand that during each week we primarily exercised the cognitive process listed in Figure 2 and all the processes below

it in the NTEO. Note that students will not work with the complete problem-solving protocol until halfway through the semester. The problems and exercises used in the course are matched with the cognitive processes that are targeted for development by using TIPP – the Taxonomy of Introductory Physics Problems (Teodorescu, Bennhold, Feldman & Medsker, 2013).

Week	Physics content	The highest cognitive process practiced	
		Information	Mental Procedures
1.	Introduction – What is physics?	Introduction – What is a thinking process?	
1.	Forces and vectors	Integrating	Executing
2.	Newton’s Laws	Symbolizing	Integrating
3.	1D Kinematics	Matching	Integrating
4.	2D Kinematics	Classifying	Matching
5.	Review and Midterm I	Review and Midterm I	
6.	Energy conservation	Analyzing errors	Classifying
7.	Collisions and momentum	Analyzing errors	Analyzing errors
8.	Rotational motion	Using ACCESS	
9.	Buoyancy and fluid flow	Using ACCESS	
10.	Review and Midterm II	Review and Midterm II	
11.	Oscillations	Using ACCESS	
12.	Waves and sound	Using ACCESS	
13.	Trying it all together	Using ACCESS	
14.	Putting all together	Why did you learn this content and these skills Where can you use the physics you learned and the abilities you acquired	
15.	Cumulative final exam	Cumulative final exam	

Figure 2. The first semester of the algebra-based introductory physics sequence. The weekly outline specifies both the physics content and the thinking process to be practiced. Here by “information” we mean declarative knowledge and by “mental procedures” we mean procedural knowledge.

The Teaching Method Used to Help Students Achieve Coherent Knowledge Structures

Helping students acquire locally and globally coherent physics knowledge is a focal point of our problem-solving training. This translates into helping them see relevant details of the knowledge within a unit, as well as the “big picture” aspect of the material. By locally coherent knowledge we mean that students perceive different pieces of knowledge as being closely related to each other. By globally coherent knowledge we mean “that students recognize sets of locally coherent knowledge as appropriate for a certain problem and useful together” (Sabella & Redish, 2007). The lack of knowledge coherence in novices has been pointed out by physics education research (Redish, 2003) and expert-novice research (Maloney, 1994; Gerace & Beatty, 2005). We have chosen to assist the students in this matter by using the cognitive processes of *categorization* and *classification*. These processes have been identified by physics education research (Beatty, Gerace, & Dufresne, 2006) as “advanced habits of mind that experts possess and students should develop”. In addition, problem classification schemes have been proven to be effective in physics instruction (Van Heuvelen, 1991).

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.

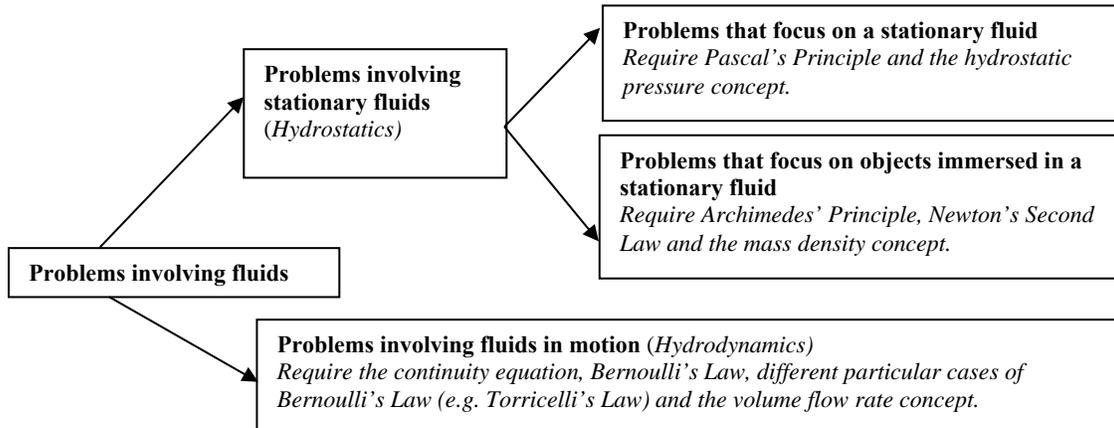


Figure 3. The problem classification scheme used for the unit on Fluids.

These classification schemes are given to students during the recitation to help them answer the “Assess the problem” step in the GW-ACCESS protocol. Students are encouraged to use the schemes for the homework problems and are expected to be able to easily identify the physics principles involved in the problem after repeated use of those schemes. The classification schemes have multiple pedagogical functions: a) to implicitly direct students’ focus towards the deep features of the physics problems 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 the diversity of physics problems is, to some extent, limited and relatively well-defined. In the middle and at the end of the semester, we hold review sessions using more complex charts that link the chapters’ content. Figure 4 shows, for example, the chart that summarizes Chapters 2-5 (featuring Newton’s 2nd Law and kinematics).

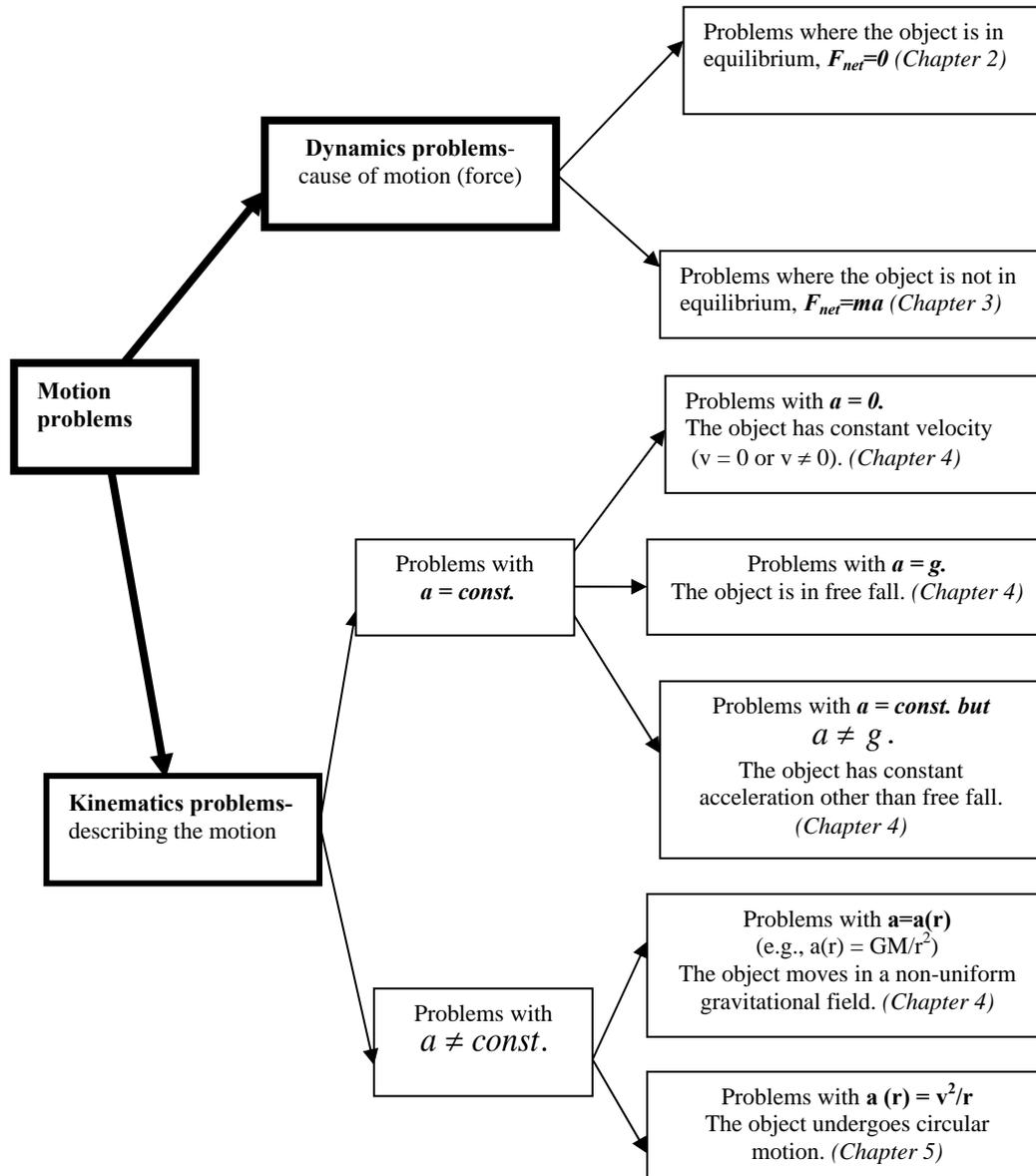


Figure 4. The problem classification scheme that is used to summarize the types of physics problems for Chapters 2-5 (which includes kinematics and forces).

The Teaching Strategy for Helping Students Solve Problems Featuring Different Contexts

Students' difficulties with physics problem solving have been extensively studied in recent years. Several results seem to be consistent across different studies: a) students perceive the same problem offered to them in symbolic and numeric forms differently, and consequently perform on it differently (Torigoe & Gladding, 2007), b) students perceive conceptual and numerical problems that involve the same physics differently, and consequently perform on them differently (Sabella, 1999), c) surface features (*i.e.* the system presented in the problem) and deep features

(i.e. the physics principle involved in the problem) are important aspects that not only differentiate the experts from novices (Chi, Feltovici, & Glaser, 1981) but also, in some circumstances, determine the extent to which students choose a certain problem-solving approach (Mestre, Dufresne, Gerace, & Hardiman, 1993). Furthermore, a natural implication for teaching is to diversify contexts and surface and deep features in the instruction. We used a small number of logical constructions, which we call *instructional sequences*, to create a variety of different contexts, problem features and corresponding thinking processes.

The *instructional sequences* are entities that combine traditional and research-based physics problems such that, during each week as students learn a new topic, they also gradually experience a new type of thinking that involves certain contexts, problem features, and cognitive processes. After students solve the problems chosen according to a certain instructional sequence, the instructor leads a guided discussion to convey to students that it is not very effective to think primarily of surface features during problem solving because the solutions should instead be triggered by deep features. In addition, we use instructional sequences to link the different curricular units, thus addressing a 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. Four types of instructional sequences have been created and are explained below. An overview of all the instructional sequences and the characteristics of physics problems they involve is shown in Table 4. The table explains what features and contexts were varied within each instructional sequence.

Figure 5 shows an example of Instructional sequence 1, while Appendix B presents other types of instructional sequences that we use. *Instructional sequence 1* blends deep features and contexts maintaining the same surface features. We used it in homework and in recitations. Figure 5 shows an example taken from recitation. The key insight here is that from week 2 to week 6 we gave students the same problem involving a skier and an inclined plane which was altered to deal with different physics principles. Also, in weeks 2 and 4 the problems were in symbolic form, while the one from week 6 was numeric.

Table 4. Summarized description of the blending of surface features, deep features and contexts in the instructional sequence. Note: **Instructional sequence 4** is not related to the other sequences. It is specifically designed to allow cognitive processes' monitoring.

Instructional sequence	Surface Features	Deep Features	Contexts	Curriculum Units
Instructional sequence 1	same	different	different	recitation, homework
Instructional sequence 2	same	different	same	homework
Instructional sequence 3	different	same	different	all
Instructional sequence 4	targets specific cognitive processes			recitation

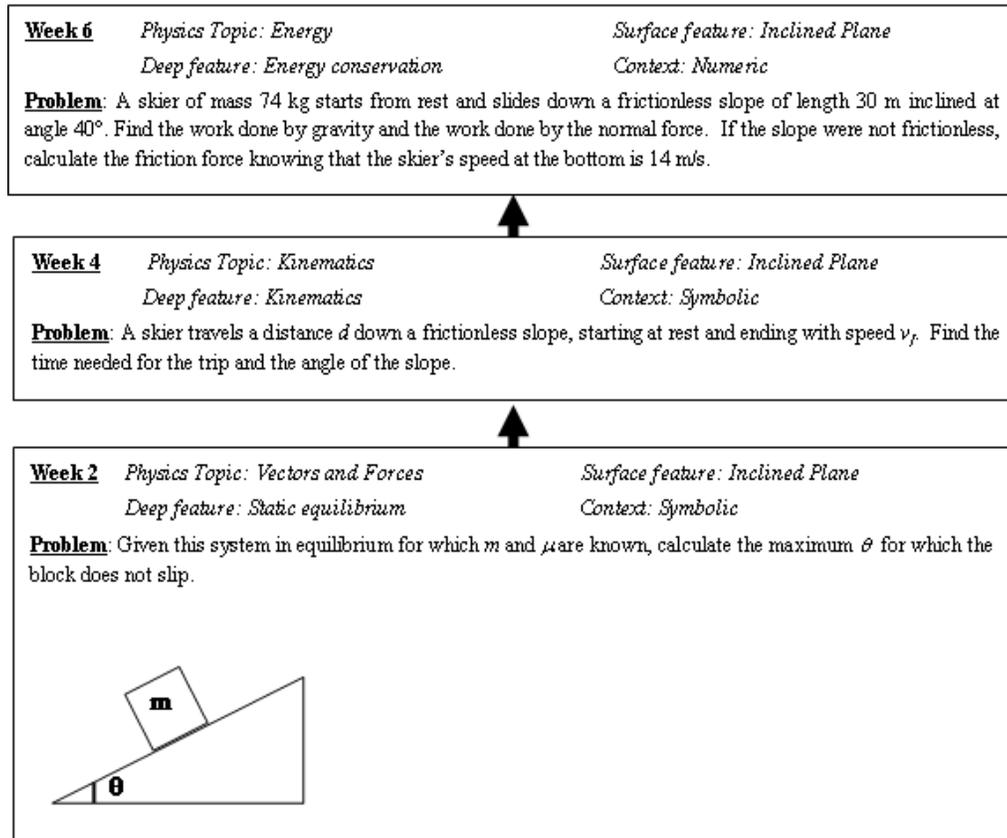


Figure 5. An example of *Instructional sequence 1* taken from recitation. Note the same surface features (inclined plane) but different contexts and deep features.

Figures 6a, 6b and 6c show the types of problems that we used in the reform curriculum. As seen in Figure 6a, while the majority of our problems are traditional (e.g. typical textbook problems), a substantial number of these problems are research-based. The research-based problems target various cognitive processes that are illustrated in Figure 6b. The definitions of these processes are the ones given in Teodorescu, Bennhold, Feldman, & Medsker, (2013). The processes shown are the highest ones involved in the research-based problems. We sought to offer students a wide variety of problems that deal with real-world situations. Figure 6c shows how we distributed those problems across the curriculum.

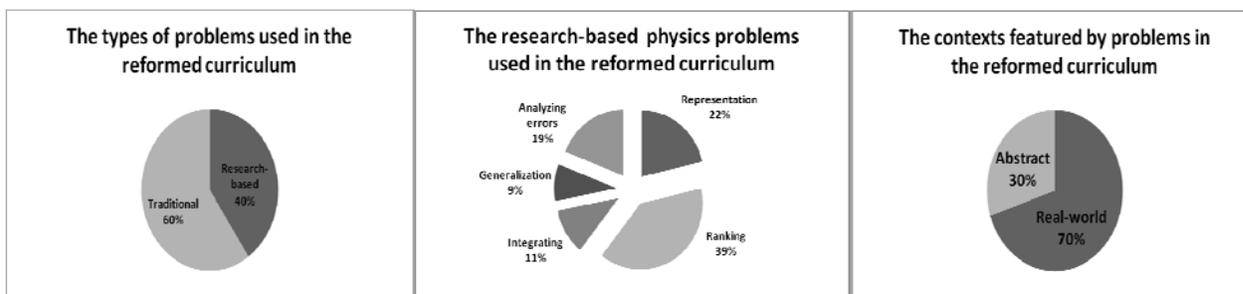


Figure 6. The problems used in recitation and homework in the reformed algebra-based curriculum. Representation tasks ask students to represent the information in various ways. Integrating problems ask students to explicitly or implicitly identify what is relevant and what is irrelevant in a problem text. Ranking tasks ask students to compare, contrast, match and rank physical quantities, scenarios or solutions. Analyzing error problems ask students to either identify errors in the problem’s text or solutions or discuss the reasonableness of the answers. Generalization problems ask students to create generalizing statements based on a sequence of tasks (Teodorescu, Bennhold, Feldman, & Medsker, 2013).

The Assessment of the GW Reformed Curriculum

To evaluate the efficacy of our pedagogy, a multi-dimensional assessment methodology was used, as outlined in Table 5:

- A problem-solving assessment based on rubrics was created specifically for this project,
- Force Concept Inventory was administered pre- and post-instruction,
- Colorado Learning Attitudes about Science Survey (CLASS) was also given to students pre- and post-instruction.

Table 5. The outcomes assessment methods

<i>Course outcomes</i>	<i>Teaching methods</i>	<i>Assessment</i>
Help students acquire conceptual understanding	Peer Instruction	Force Concept Inventory
Help students improve their problem-solving performance	GW-ACCESS protocol Problem classification schemes that summarize the information and mental procedures Instructional sequences	Rubrics
Help students improve their attitudes towards learning physics	Allotted lecture time to point out when, where and how students can use both the content and the abilities learned	Colorado Learning Attitudes about Science Survey

The Assessment of Students' Problem-Solving 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 numeric scores, with the highest level reflecting perfect completion of a task or total proficiency in the area being evaluated (Brookhart, 1999). They provide a relatively unbiased, quantitative way to examine different steps in student work. 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. For the purpose of this project, we have chosen rubrics as a straightforward method of measuring the improvement of student performance in component processes as applied to solving a physics problem, independent of their performance in other parts of the problem-solving process.

In-depth work with assessment rubrics has been done by the Physics and Astronomy Education Research (PAER) group at Rutgers University. The group developed rubrics for the assessment of seven scientific abilities, which they define as the most important procedures, processes, and skills scientists use when constructing scientific knowledge and when solving experimental problems (Etkina, Van Heuvelen, White-Brahmia, Brookes, Gentile, Murthy, Rosengrant, & Warren, 2006). Each rubric has a range of scores from 0 to 3, with 0 (missing), 1 (inadequate), 2 (needs improvement), or 3 (adequate). We followed their idea and designed rubrics to evaluate the different steps involved in solving a physics problem and we applied them to the problem below. We used rubrics to grade students' quizzes throughout the semester; in addition, we gave them the problem below after Newton's 2nd Law was learned early in the semester and also in the final exam at the end. Students were asked to solve it following the *GW-ACCESS* protocol. Separate rubrics were used to grade the four parts: *Assess the problem*, *Create a drawing*, *Conceptualize the strategy* and *Execute the solution* parts. The *GW-ACCESS* parts were graded with rubrics developed following the model of Etkina and her colleagues (2006).

Assessment Problem: Two blocks of masses $M_1 = 8 \text{ kg}$ and $M_2 = 20 \text{ kg}$ are connected as shown in Figure 7 below. The two inclined planes are frictionless. The string is inextensible and both the pulley and the string have negligible mass. Knowing the angles $\theta = 60^\circ$ and $\beta = 30^\circ$, find the acceleration of each block and the tension in the string.

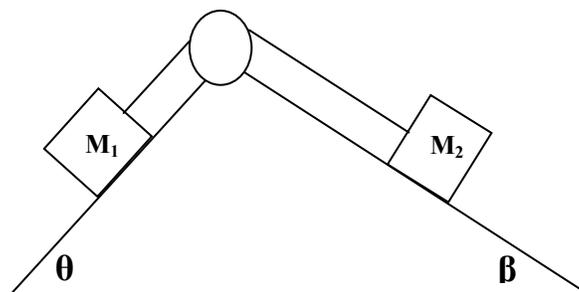


Figure 7. Modified Atwood machine.

Figures 8-11 illustrate the rubrics used to evaluate students' abilities and the positive shifts in students' performance for each of the abilities targeted. The gain indicated in the figures is the difference between the post- and pre- distribution means. The grading was performed by one grader and therefore no inter-rater reliability testing was necessary.

The results for *Assess the problem* step are shown in Figure 8. They indicate the highest gain in students' performance as compared with the other abilities. This may suggest that, among the abilities taught, this one seems to be the best learned by the students. This can also be an indication of the effectiveness of our classification schemes. Also, the pre-test mode distribution is 2, as compared to the pre-test mode distribution for the other abilities, which is 1. This indicates that, even before instruction, students seem better prepared to assess a problem than to create the corresponding drawing and strategy and to solve it. The results for *Create a drawing* step are shown in Figure 9. They indicate the lowest gain in students' performance as compared with the other abilities. This may suggest that, among the abilities taught, this one seems to be the hardest to learn for students. The results for *Conceptualize the strategy* step are shown in Figure 10. They indicate the second highest gain in students' performance. This gain, associated with the low pre-test distribution mode (which is 1), may imply that students made good progress in learning this ability. The results for *Execute the solution* step are shown in Figure 11. They indicate a moderate gain in students' performance. It should be noted that the assessment problem we used is considered a difficult problem for algebra-based physics students. The moderate gain we achieved can be due to the difficulty of this problem.

<u>Scientific Ability</u>	<u>Missing (0)</u>	<u>Inadequate (1)</u>	<u>Needs improvement (2)</u>	<u>Adequate (3)</u>
<i>Is able to assess (categorize) the problem according to deep features (the underlying physics concepts or principles).</i>	No attempt is made to assess the problem.	The problem is assessed incorrectly or according to surface features.	The problem is assessed correctly but too generally (according to a concept and not a principle).	The problem is assessed according to correct physics concepts and/or principles.

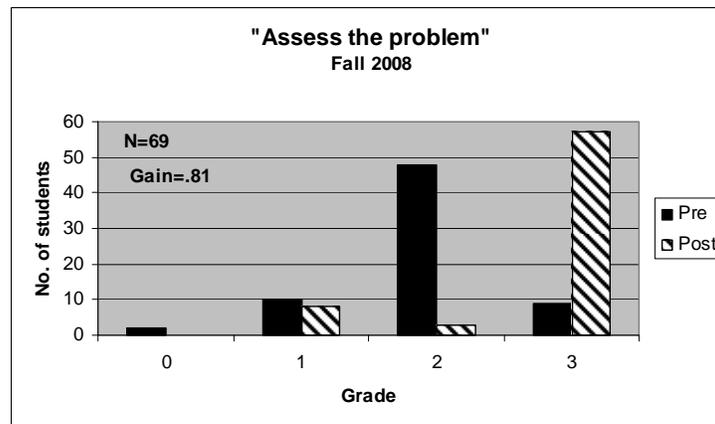


Figure 8. The rubric used to evaluate the *Assess the problem* ability and students' scores.

<u>Scientific Ability</u>	<u>Missing (0)</u>	<u>Inadequate (1)</u>	<u>Needs improvement (2)</u>	<u>Adequate (3)</u>
<i>Is able to draw the corresponding free-body diagram correctly.</i>	No FBD is constructed.	FBD is constructed but contains major errors such as incorrect force vectors, wrong direction, extra incorrect vectors, or missing vectors.	FBD contains no errors in vectors but lacks a key feature such as labels of forces or axes are missing.	The FBD contains no errors and each force is labeled so that it is clearly understood what each force represents. Axes are present.

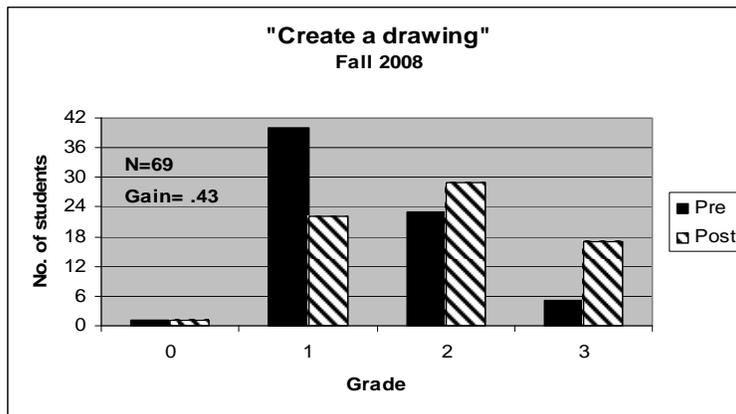


Figure 9. The rubric used to evaluate the *Create a drawing* ability and students' scores.

<u>Scientific Ability</u>	<u>Missing (0)</u>	<u>Inadequate (1)</u>	<u>Needs improvement (2)</u>	<u>Adequate (3)</u>
<i>Is able to identify the necessary steps required to solve the problem.</i>	No attempt is made to write a strategy.	The strategy is either too generic or wrong.	The strategy contains some correct steps pertaining to the problem but critical information is missing.	The strategy contains the necessary steps and critical information to solve the problem.

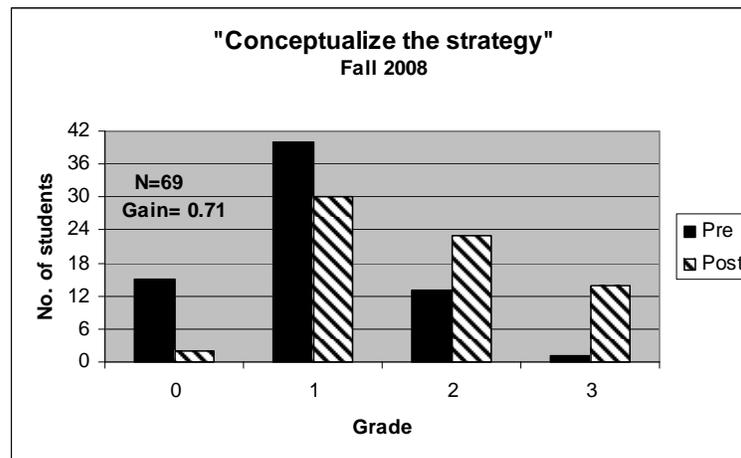


Figure 10. The rubric used to evaluate the *Conceptualize the strategy* ability and students' scores.

<u>Scientific Ability</u>	<u>Missing (0)</u>	<u>Inadequate (1)</u>	<u>Needs improvement (2)</u>	<u>Adequate (3)</u>
<i>Is able to execute the necessary steps required to solve the problem.</i>	No attempt is made to execute the solution symbolically.	The solution contains mostly wrong equations or only numerical equations. No attempt is made to solve the problems symbolically.	The solution contains some good equations, but some equations are wrong.	The solution contains all correct equations.

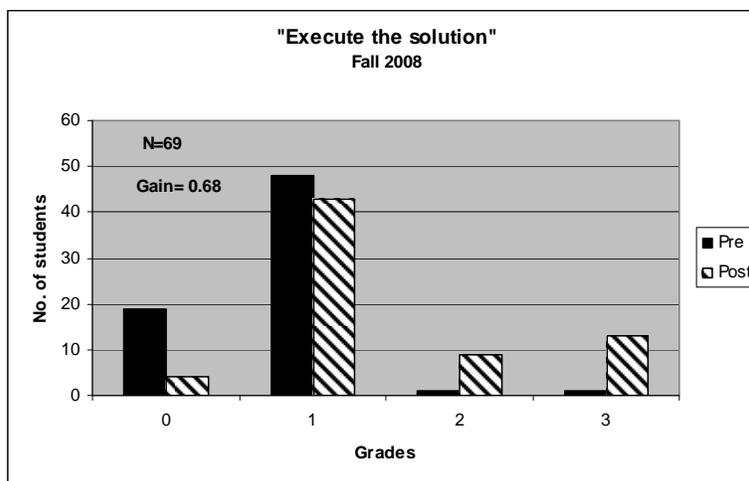


Figure 11. The rubric used to evaluate the *Execute the solution* ability and students' scores.

Table 6 shows the positive shifts obtained after the instruction for all these abilities. They are statistically significant ($p = .0001$, Wilcoxon nonparametric test) and suggest that students' problem-solving behavior has improved. Student post-instruction performance was the highest on the *Assess the problem* ability (Figure 8) and the lowest on the *Execute the solution* ability (Figure 11). The highest gain was achieved for *Assess the problem* ability and the lowest for *Create a drawing* ability (Figure 9). Moderate improvements were found in the other abilities.

Table 6. The class pre and post means and the absolute gain (post – pre) for each ability.

<i>Ability</i>	<i>Pre</i>	<i>Post</i>	<i>Gain</i>
A ssess the problem	1.93	2.72	0.79
C reate a drawing	1.46	1.90	0.44
C onceptualize the strategy	1.00	1.71	0.71
E xecute the solution	0.77	1.45	0.68

The Assessment of Students' Attitudes About Learning Physics

It is well known that what students believe about physics as a science and what they expect from their physics courses determine their attitude and motivation towards the process of learning physics. Ultimately, those factors influence their overall achievement in a physics course. The most common instruments for measuring students' expectations, beliefs and attitudes in physics courses are the MPEX (Redish, Steinberg, & Saul, 1998), VASS (Halloun & Hestenes, 1996), CLASS (Adams, Perkins, Podolefsky, Dubson, Finkelstein, & Wieman, 2006) and EBAPS (Elby, 2001). As stated at the beginning of this paper, one of the learning objectives for our introductory physics course is not only to enhance students' problem-solving abilities but also to influence their attitudes about learning physics. One of the recently developed instruments to measure such beliefs and attitudes is the Colorado Learning Attitudes about Science Survey (CLASS). We administered this survey in Fall 2008 and the results are shown in Table 7. Overall, they indicate a generally positive trend, compared to the negative trend reported in the literature. These shifts suggest that students exhibit more expert-like attitudes at the end of the instruction compared to the beginning, in six out of eight categories. Traditional lectures have been reported to generate shifts on the overall CLASS of -8.2% to $+1.5\%$ for calculus-based courses, shifts of 1% for non-science majors and -9.8% for algebra-based courses for premedical students (Perkins, Adams, Pollock, Finkelstein, & Wieman, 2005).

Table 7. Results for CLASS survey administered in Fall 2008. Positive gains have been achieved, indicating changes in students' views towards more expert-like views. (Standard error is given in parentheses.)

Category	Pre	Post	Shift (Diff. of averages)
Overall	63.9 (1.88)	69.5 (1.93)	5.6 (1.3)
Real-world connections	68.8 (3.84)	83.1 (3.20)	14.2 (4.0)
Personal interest	65.6 (3.33)	71.8 (3.43)	6.2 (3.0)
Sense-making effort	74.9 (2.43)	73.0 (2.70)	-1.9 (2.3)
Conceptual understanding	59.2 (3.28)	62.6 (3.80)	3.4 (3.1)
Applied conceptual understanding	46.3 (3.00)	56.5 (3.47)	10.2 (3.1)
Problem solving (general)	74.2 (2.82)	75.8 (2.85)	1.5 (2.4)
Problem solving (confidence)	71.5 (3.33)	76.5 (3.71)	5 (3.5)
Problem-solving (sophistication)	52.5 (3.81)	59.5 (3.64)	7 (3.4)

In the course evaluations, students ranked the usefulness of the lectures as 4.28/5 and of the recitations as 3.34/5, which is an improvement as compared to previous semesters when the usefulness of the lectures was ranked as 3.40/5 and of the recitation as 2.76/5.

Conclusions

We presented in this paper the reform approaches that we created to enhance students' problem-solving performance and improve their learning attitudes in our introductory algebra-based curriculum. Several comments are worth mentioning here about the course. To promote systematic problem solving, we had to challenge the students with complex problems. The appropriate level of complexity was determined according to the specifics of our student population. Problems that were too difficult discouraged students, while easy ones sent the message that they had enough knowledge and did not need to learn anything new. Facing hard problems, students tend to be discouraged in the beginning; therefore the instructor and the teaching assistants have a critical role in helping them overcome this initial frustration in a constructive way.

A second issue is related to problem selection and implementation of the *GW-ACCESS* protocol. To help students accept and learn how to use this protocol in a natural way, we not only broke it into steps and gradually offered it to students, but we also made sure that the problems we used in recitation in a particular week reflected the cognitive processes that we wanted the students to learn in the *GW-ACCESS* step. Furthermore, this was reinforced by the exam problems, which had formats similar to the recitation problems.

A third aspect, related to the problems used, is that we tried to offer problems that have features similar to problems previously solved by students. This was done using the instructional sequences. An expert will easily find the common features of the problems belonging to each of the instructional sequences presented. However, from our experience, students have to be constantly prompted and explicitly shown the link between the problems. Otherwise, they perceive them as very different problems with no common features.

Regarding student dispositions, as the semester went on, we explicitly addressed the need for learning problem solving. In this way, we aimed to help students appreciate their efforts, thus increasing their motivation and self-esteem. We did not initiate such discussions early in the semester, because we found that this has a detrimental effect on students' attitudes. Our semester starts with the entire focus on physics in general and after four or five weeks we begin to spend 10-15 min of lecture time to talk in more depth about problem solving. We discovered the beneficial impact of a final lecture that clearly explains the wide range of employment opportunities that require introductory physics knowledge, the demands for problem-solving abilities stated in political, educational, and social reports; and the problem-solving abilities that are becoming mandatory for employment according to national surveys. In addition, in our final lecture, we remind the students when and how we practiced all these abilities in our course. We conclude with everyday examples in which variations of the *GW-ACCESS* protocol can be used to solve complicated and demanding life problems.

Teaching Assistant (TA) training is a key component of success in our classes. TAs do not automatically understand the philosophy behind this course, especially when they teach it for the first time. While the physics content is usually familiar to them, they have difficulties understanding why we use the specific problems and not the standard textbook problems. Open dialog, continuous assistance and clear explanations of the pedagogy, along with precise teaching guidance, are often enough to help them become comfortable and proficient with this instruction.

Regarding the assessment of our course, it should be noted that our design made possible a detailed evaluation of the key steps involved in basic physics problem solving. We consider the

traditional grading method based on “correct answers” important. However, we often observed that many students perform various steps related to a problem correctly, even when they do not manage to obtain the right answer. We hope that our tool, together with other existing assessments (Adams & Wieman, 2006; Docktor, 2009; Cummings & Marx, 2010), will enable the instructors to better evaluate students’ problem-solving performance.

The results we obtained in all the assessments are encouraging: they show improvement in student problem-solving abilities and their attitudes. CLASS administered pre- and post-instruction revealed that student’ beliefs have changed in a positive way. Students seem to realize the connection between the physics they learned and the real world better after the instruction and believe that they can apply the concepts they learned. During the instruction, they built confidence in their problem-solving ability and their interest was stimulated.

Future work will seek to continue the refinement and assessment of this course. Using the existing assessments, we intend to build a longitudinal database in order to document the successes and limitations of our methodology. In addition to the ones we used, more assessments have to be implemented to evaluate aspects of our instruction that have not been documented at this stage, including the following:

1. The remaining *GW-ACCESS* steps (*Scrutinize your results* and *Sum up your learning*) for which the rubrics are not yet finalized;
2. An analysis of the connections between students’ responses on each step of the *GW-ACCESS* protocol, to judge the extent to which they are grasping the whole problem-solving process;
3. The laboratory activities (which can be evaluated using the method described by Etkina and her colleagues (2006));
4. The coherence of students’ knowledge (which can be evaluated using the method described by Sabella (1999));
5. Students’ meta-cognitive behavior, which we recently started to monitor in one pilot lab section.

The refinement of the course will aim to help students achieve more significant improvements in their conceptual understanding.

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APPENDIX A: The GW-ACCESS Protocol

A – Assess the problem

What is your first impression of the problem? Can you verbalize what the problem is actually asking you to do?

- Identify the physics principles needed to solve the problem. Physics principles are described by words like *momentum conservation*, *energy conservation*, *Newton's 2nd Law*, etc. If principles are not involved in the problem, identify the concepts that are needed to solve the problem. Physics concepts are described by words like *torque*, *momentum*, *work*, etc.

C – Create a drawing

Translate the words of the problem into a diagram or a picture that contains clues for how to solve the problem. A drawing can be:

- A free-body diagram (FBD) that displays the forces that act on an object.
- A diagram that displays the motion of an object chronologically.
- A diagram that compares the initial and final states of an object, *e.g.*, for energy and momentum conservation.

C – Conceptualize the strategy

Develop a strategy that outlines the steps you need to follow to solve the problem. The signature of a good strategy is that you could give your strategy to someone else who could then solve the problem. Thus a good strategy addresses the following questions:

- Does the problem need to be broken into parts, either because there are several objects or because the same object experiences different kinds of motion?
- What physics principles apply to each part and how do they apply to the specifics of the problem?
- What is the key insight that is needed to solve the problem or each part of the problem?
- How do the parts link together to give you the solution of the whole problem?
- What are the relevant equations that represent the physics principles that you've outlined?
- What are the known and unknown quantities of the problem?

E – Execute the solution

Now that you've done the setup of the problem solution, you have to go through the steps you've outlined to reach the answer.

- Solve the equations algebraically for the unknown variable that you are looking for. Show all your algebraic steps explicitly in symbolic form (no numbers yet!). Make sure that your unknown quantity is expressed in terms of known variables.
- Plug in the numerical values given in the problem to obtain your final answer. This may involve getting an intermediate result and then using that number in a subsequent part.

S – Scrutinize your results

You need to do a "reality check" to make sure that your answer is sensible.

- Check your units.
- Are the numerical values you got reasonable?
- Compare the situation presented in the problem with a real-world situation.
- Try some limiting cases.

S – Sum up your learning

This is the time to reflect on the purpose of this exercise. This helps put the exercise into a larger context, in the overall framework of physics, for one thing, and also in the ongoing evolution of your own learning.

- How did this problem link to a physics concept which is a part of a greater whole?
- How did this problem help you to improve your problem-solving skills? How did this problem apply the laws of physics to a real-life situation?

APPENDIX B: Instructional Sequences

Instructional sequence 2 featured in Figure 12 combines problems having the same surface features and contexts but different deep features. It was used in recitation and homework. The system presented is always the bungee jumper and the context is always numerical, but the physics principle involved in each of the problems is different.

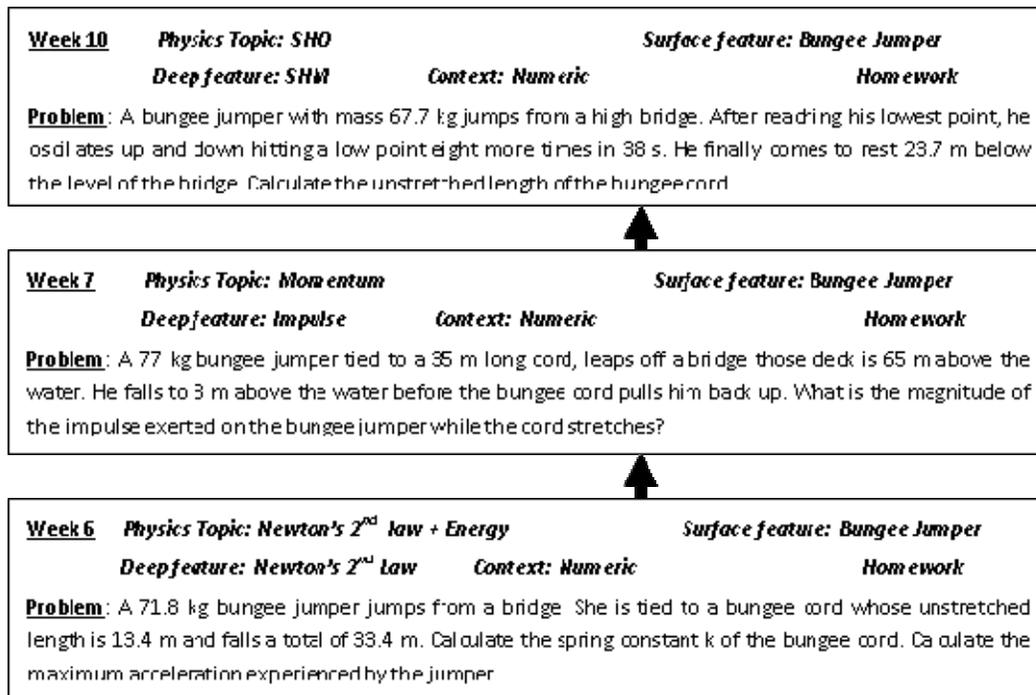


Figure 12. An example of *Instructional sequence 2* taken from homework. Note the same surface features (bungee jumper) and context (numerical) but different deep features.

Instructional sequence 3 shown in Figure 13 brings together problems having the same deep features but different surface features and contexts. We used it to link two or more curriculum units. Note how a symbolic problem related to Newton's 2nd Law given in week 2 in recitation is followed by numeric problems involving Newton's 2nd Law and the same free-body diagram given in the homework. All these problems need similar free-body diagrams.

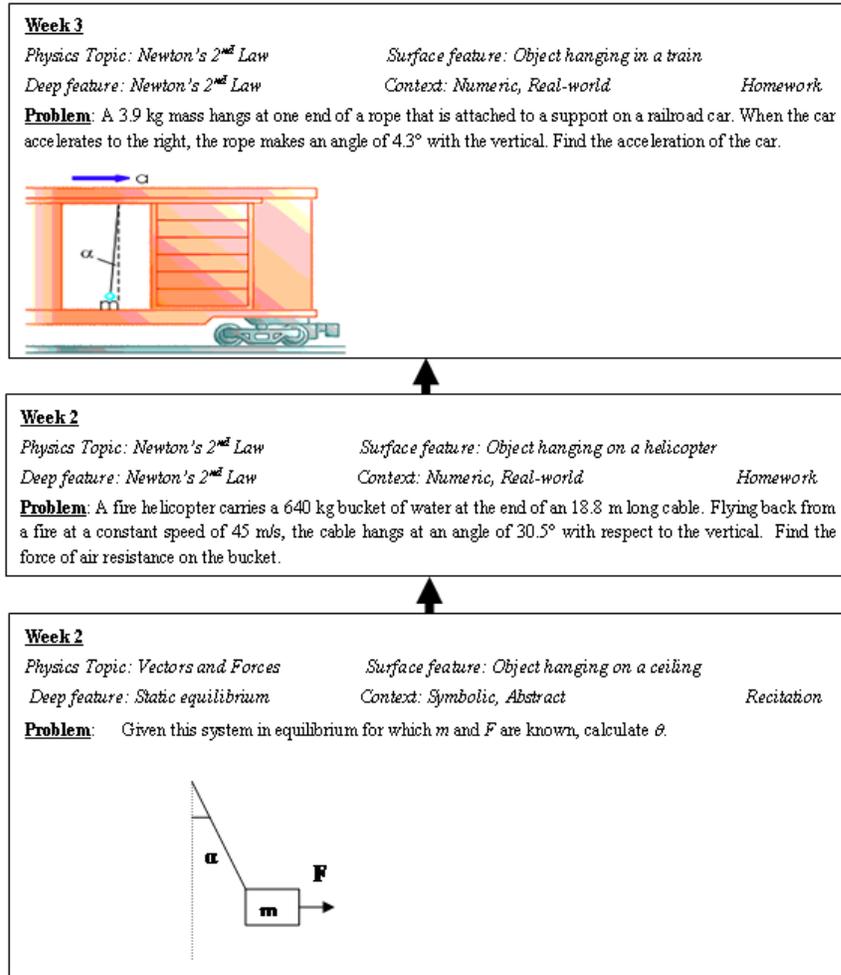


Figure 13. An example of Instructional sequence 3 that combines problem from recitation and homework. Note the same deep features (Newton's 2nd Law, the same free-body diagram), but different surface features (helicopter and train) and contexts (symbolic and numeric, abstract and real-world).

Instructional sequence 4 was designed to have students practice specific cognitive processes in addition to the thinking triggered by the above progressions. The cognitive 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 14 shows an example in which students exercise processes like creating a strategy, ranking of information and analyzing errors related to information. We used this instructional sequence in the recitation sessions.

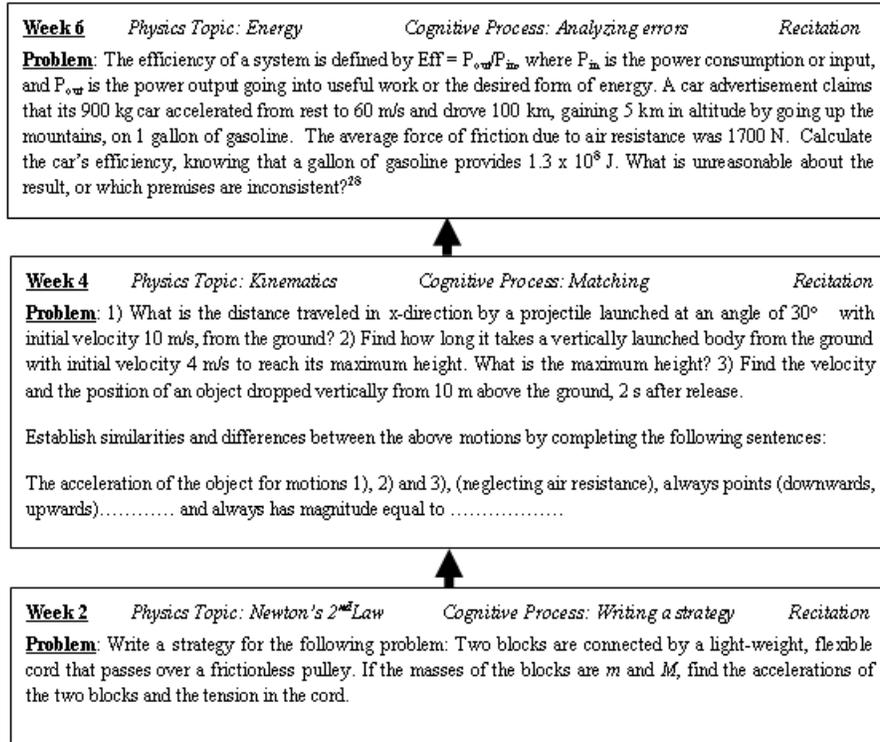


Figure 14. An example of Instructional sequence 4 taken from recitation. Note how the cognitive processes targeted increase in complexity as more content is taught from week 2 to week 6.

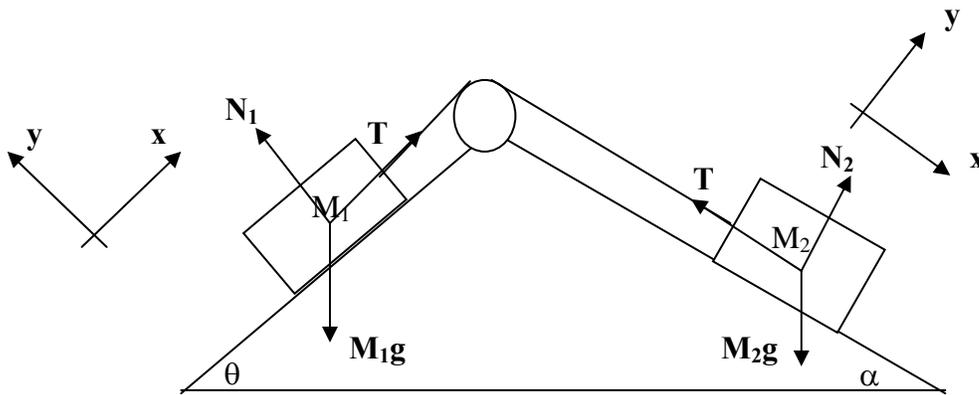
APPENDIX C

Proposed solution for the Example assessment problem. The solution that is considered to be correct is presented below.

A – Assess the problem

This is a Newton’s 2nd Law problem.

C – Create a drawing



C – Conceptualize the strategy

I treat each object separately. I apply Newton’s 2nd Law for each object: $\Sigma F_x = ma$ $\Sigma F_y = 0$

Key insights: Both objects move with the same acceleration. The same tension acts on both objects. The coordinate system should be tilted for convenience.

Known: $M_1=8$ kg, $M_2=20$ kg, $\theta= 60^\circ$, $\alpha= 30^\circ$

Unknown: T, a

E – Execute the solution

$$(M_1) \Sigma F_x = M_1 a \qquad T - M_1 g \sin \theta = M_1 a \quad (A)$$

$$(M_2) \Sigma F_x = M_2 a \qquad M_2 g \sin \alpha - T = M_2 a \quad (A)$$

$$T = M_1 g \sin \theta + M_1 a \quad (B)$$

$$a = \frac{(M_2 \sin \alpha - M_1 \sin \theta)}{(M_1 + M_2)} g \quad (B) \qquad a = 1.07 m/s^2 \quad (C)$$

$$T = M_1 g \sin \theta + \frac{M_1 (M_2 \sin \alpha - M_1 \sin \theta)}{(M_1 + M_2)} g \quad (B) \qquad T = 76.57 N \quad (C)$$