An Approach to Enhance the Teaching of Undergraduate Science and Engineering Introductory Physics Courses

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1 Motivation

2 The proposed method

3 Discussion and Conclusions

4 Reading Sources
Motivation

A word of caution

If the trend of teaching Physics via an overemphasis on conceptual reasoning over the development of quantitative reasoning is adopted by curriculum developers of undeveloped countries, no doubt that it will have a negative impact on the development of the sciences in those countries. In fact, while industrialized countries have resources to deal with the side effects of this trend, undeveloped countries does not.

Recall that it is in Physics courses where students are trained in using what they learned in their math classes, and even are trained in new non-standard approaches to perform computations such as the use of dimensional analysis.
Moreover, the large number of published “Comment on …” and “Reply to …” articles, in which much of the discussion is based on the incorrectness of the physical interpretation of a concept or an idea, are indicative that the “qualitatively understanding of the concepts of physics” [Hobson, 2006] is a very elusive concept, consequently, extremely difficult to teach and which even experts can fail to grasp [Singh, 2002].
On the character of Physics

As expressed by Lord Kelvin, quoted by Hewitt [Hewitt, 1993],

“I often say that when you can measure something and express it in numbers, you know something about it. When you can not measure it, when you can not express it in numbers, your knowledge is of a meager and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science, whatever it may be.”
On the character of Physics

In letters encouraging prospective students of Physics, the Nobel prize-winning and great physicist Lev Davidovich Landau, was also emphatic on this matter [Lifshitz, 1977]:

“You must start with mathematics which, you know, is the foundation of our science. [...] Bear in mind that by ’knowledge of mathematics’ we mean not just all kinds of theorems, but a practical ability to integrate and to solve in quadratures ordinary differential equations, etc.”
The thoughts of these great physicist are very precise on the nature of Physics: It is an intrinsically experimental science aiming to explain nature’s behavior from a quantitative point of view. And this fact, I believe, was actually the one that triggers the Galileo’s affair with the Catholic Church in the 17th century.
On the character of Physics

One can even think on that matter from the following:

- Kepler needed to be very precise quantitatively to take a data point that missed by *Eight Minutes of Arc* the circular orbit. As Kepler wrote “... For, if I had believed that we could ignore these eight minutes, I would have patched up my hypothesis accordingly. But since it was not permissible to ignore them, those eight minutes point the road to a complete reformation of astronomy.”[Koestler, 1959]

- The calculation by Einstein that light passing the sun would deviate from its straight-line path through an angle of 1.75 *arc seconds*. 
On the character of Physics (continued · · ·)

In spite of this, as recently discussed in an author’s letter published in the *American Journal of Physics* [Rojas, 2009], most of the recent published articles in *Physics Education Research* favors an emphasis on conceptual learning over quantitative reasoning [Hobson, 2006; Hoellwarth et al., 2005; Mualem & Eylon, 2007; Sabella & Redish, 2007; Walsh et al., 2007].
Thus, one might wonder whether the impact of this trend on students is that they fail to answer correctly quantitative questions involving simple standard computations [Boudreaux et al., 2008; Flores et al., 2004; Meredith & Marrongelle, 2008; Mul et al., 2004; Rimoldini & Singh, 2005; Rojas, 2008; Yerushalmi & Magen, 2006].

Moreover, the analysis of published research also shows that students lack of a consistent and coherent structured methodology for solving physics problems [Hammer, 1996; Rimoldini & Singh, 2005; Sabella & Redish, 2007; Walsh et al., 2007].
Evidence against problem solving

One can look at some published interview excerpts regarding the think-aloud method about solving problems. While experts show the use of a clear structured way of approaching problems, students do not show any [Sabella & Redish, 2007; Walsh et al., 2007].

From a quantitatively point of view, one can obtain information by looking at published data used to measure other aspects of the teaching and learning process:

### From the CLASS survey [Adams et al., 2006]

**Table:** CLASS V.3 results for a calculus-based Physics I course (N=397)

<table>
<thead>
<tr>
<th>Category</th>
<th>pre</th>
<th>post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>65%</td>
<td>59%</td>
</tr>
<tr>
<td>Real world connections</td>
<td>72%</td>
<td>65%</td>
</tr>
<tr>
<td>Personal interest</td>
<td>67%</td>
<td>56%</td>
</tr>
<tr>
<td>Sense making/effort</td>
<td>73%</td>
<td>63%</td>
</tr>
<tr>
<td>Conceptual connections</td>
<td>63%</td>
<td>55%</td>
</tr>
<tr>
<td>Applied conceptual understanding</td>
<td>53%</td>
<td>47%</td>
</tr>
<tr>
<td>Problem solving general</td>
<td>71%</td>
<td>58%</td>
</tr>
<tr>
<td>Problem solving confidence</td>
<td>73%</td>
<td>58%</td>
</tr>
<tr>
<td>Problem solving sophistication</td>
<td>61%</td>
<td>46%</td>
</tr>
</tbody>
</table>
The CLASS survey: questions measuring *Problem solving confidence*

15. If I get stuck on a physics problem on my first try, I usually try to figure out a different way that works.

16. Nearly everyone is capable of understanding physics if they work at it.

34. I can usually figure out a way to solve physics problems.

40. If I get stuck on a physics problem, there is no chance I’ll figure it out on my own.

“Students attitudes and approaches to problem solving in physics can profoundly influence their motivation to learn and development of expertise.” [Mason & Singh, 2010]

“Students’ expectations are better predictors of college science performance than the amount of high-school science or math they completed.” [Adams et al., 2006]
Teaching: is a deliberate assistance provided to facilitated learning. The teacher or instructor could be a human, a robot, or a book in the case of self-teaching. A major problem is when teaching occur without any learning, a situation unfortunately that seems to be too frequent.

(a) Initial Performance: What kinds of things do we know or one is able to do in the initial state $S_i$?

(b) The learning stage: It happens when one is taken from $S_i$ to $S_f$ (one is able to do things in $S_f$ that we were unable to do in $S_i$).

(c) Final Performance: After the occurrence of some learning, What kinds of things do we know or one is able to do in the final state $S_f$? What kinds of underlying knowledge or thought processes lead to this final performance?
A couple of problems

Some research have even shown that students eventually emerge from those courses with fragmented knowledge and without the problem-solving abilities needed to apply their acquired scientific knowledge [Halloun & Hestenes, 1985].

“Instead of identifying underlying mechanisms (processes and structures) responsible for the observable phenomena, most attempts to improve science education have tried to devise more effective teaching methods or to deal with students’ scientific misconceptions. Thus in science education the primary interest is not focused on the science itself, but on students who are trying to learn scientific knowledge and thinking.” [Reif, 2008]
Project: Reasoning Resources in Math and Physics

“The time is ripe for better integration of theories of learning and applications to pedagogical development throughout the undergraduate science curriculum. Studying learning in physics will help researchers understand what triggers and connects elements of student reasoning when intuitions and everyday thinking interact with appropriate verbal, graphical, and mathematical formalism.” (PER at UMaine)
Motivation

The proposed method

Discussion and Conclusions

Reading Sources
Inspired on Polya’s ideas [Polya, 1973], a six steps problem-solving strategy is proposed that could be applied to tackle the afore mentioned problems in the teaching and learning of physics [Rojas, 2010].

The strategy can be used for teaching both conceptual and quantitative reasoning explicitly, particularly if combined with fruitful ideas advanced in relation to the design of instruction that triggers the involved learning cognitive mechanism, leading to more effective outcomes in the teaching and learning process of Physics [Dunn & Barbanel, 2000; Hestenes, 2003; Redish & Steinberg, 1999; Reif, 1981, 2008; Reif & Scott, 1999; Scherr, 2007; Singh, 2009].

By proper training, students could absorb the steps of the problem-solving strategy in such a way that they could perform the corresponding operations mentally, naturally, and vigorously.
## The strategy

<table>
<thead>
<tr>
<th>Steps to follow</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Understand what the problem is.</td>
</tr>
<tr>
<td>2</td>
<td>Provide a qualitative description of the problem.</td>
</tr>
<tr>
<td>3</td>
<td>Plan a solution.</td>
</tr>
<tr>
<td>4</td>
<td>Carrying out the plan.</td>
</tr>
<tr>
<td>5</td>
<td>Verify the internal consistency and the coherence of the used equations.</td>
</tr>
<tr>
<td>6</td>
<td>Check and evaluate the obtained solution</td>
</tr>
</tbody>
</table>

**Remark 1**: The order does not matter. Using inductive reasoning one could start from a solution and ask which problem is it solving.

**Remark 2**: Why 6 steps and not 5, as it is usually presented in textbooks? Experience shows that one too often does not verify the internal consistency and coherence of the equations being solve. And this mistake is also found to be performed by textbook writers, as discussed in [Bohren, 2009; Sandin, 1973].
Step 1: Understand the problem

“It is foolish to answer a question that one does not understand. ... But [one] should not only understand it, [one] should also desire its solution.” [Polya, 1973]

Some questions that could be asked to better understand the problem are like: What is the unknown? What is the condition? Is it possible to satisfy the condition? Is the condition sufficient to determine the unknown? Or is it insufficient? Or redundant? Or contradictory? Making a drawing could be of help too.

In this stage one needs to actually be sure to what the problem is. Perhaps one also would need to reformulate the problem in our own words, making sure of obtaining all the giving information for solving the problem. This is a crucial step in the sense that if we do not know where are we going, any route will take us there.
Step 2: Provide a qualitative description of the problem

In this stage one needs to think and write down the laws, principles, or possible formulations that could help us to solve the problem (i.e. Newton’s law, energy conservation, momentum conservation, theorem of parallel axis for computing inertia moment, non-inertial reference system, etc.). If necessary, the drawings of the previous step could be complemented by the corresponding problem free-body and/or vector diagram.
Step 3: Plan a solution

This step involves looking at the unknown and trying to think of a familiar problem having the same or a similar unknown. Some questions to be ask are like: Have you seen this before? Or have you seen the same problem in a slightly different form? Is the information at hand enough to get a solution?

“We have a plan when we know, or know at least in outline, which calculations, computations, or constructions we have to perform in order to obtain the unknown. · · · We know, of course, that it is hard to have a good idea if we have little knowledge of the subject, and impossible to have it if we have no knowledge. · · · Mere remembering is not enough for a good idea, but we can not have any good idea without recollecting some pertinent facts.”[Polya, 1973]
Step 4: Carrying out the plan

At this stage one needs to define an strategy to solve the relevant equations leading to the solution of the problem, avoiding as much as possible to plug numbers in the respective equations. Perhaps one would need to go back in order to find an easier mathematical formulation of the problem.
Step 5: Verify the internal consistency and the coherence of the used equations

“Check each step. Can you see clearly that the step is correct? Can you prove that it is correct? · · · Many mistakes can be avoided if, carrying out the plan, one checks each step.”[Polya, 1973]

One needs to verify whether the equations are consistent with what they represent (i.e. are the equations dimensionally correct? Do the quantity represents a volume or a surface? Is it a dimensionless number?).

After verifying no inconsistencies are found in the mathematical solution of the problem, one could then plug numbers to see if the obtained values make sense.
Step 6: Check and evaluate the obtained solution

“Some of the best effects may be lost if the student fails to reexamine and to reconsider the completed solution.”[Polya, 1973] Thus, once a solution has been obtained, its plausibility needs to be evaluated.

Some questions could be asked in this regards: can the results be derived differently? Can the result or the method be applied to solve or fully understand other problems? Can the solution be used to write down the solution of a less general problem? Can the solution be used to further understand the qualitative behavior of the problem? Is it possible to have a division by zero by changing a given parameter? Does it makes sense?, and so forth.
Outline

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Concluding remarks

The presented problem-solving strategy is a consistent and coherent methodological framework for teaching physics which integrates both aspects, conceptual and mathematical reasoning, in a systemic way of thinking, aiming to tackle two major problems in the learning and teaching of physics:

1. The students’ need for a suitable methodological framework that could help them to fill the textbooks’ gap on enhancing their mathematical reasoning abilities, which are essential for reinforcing students’ knowledge of conceptual physics.

2. A deficiency in the teaching of physics leading to students not being taught a coherent physics problem-solving strategy that enables them to engage in both mathematical and conceptual reasoning.
A word of caution

If the trend of teaching Physics via an overemphasis on conceptual reasoning over the development of quantitative reasoning is adopted by curriculum developers of undeveloped countries, no doubt that it will have a negative impact on the development of the sciences in those countries. In fact, while industrialized countries have resources to deal with the side effects of this trend, undeveloped countries does not.

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Some enlightenment thoughts

Let’s finish by recalling two “axiomatic thoughts” about the art of teaching and learning that the great mathematician G. Polya used to stress very much:

“For efficient learning, the learner should be interested in the material to be learnt and find pleasure in the activity of learning.”

“We know from painful experience that a perfectly unambiguous and correct exposition can be far from satisfactory and may appear uninspiring, tiresome or disappointing, even if the subject-matter presented is interesting in itself. The most conspicuous blemish of an otherwise acceptable presentation is the ’deus ex machina’.”
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