Learning Physics: a Competency-based Curriculum using Modelling Techniques and PBL Approach

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As pointed out by the OECD Global Science Forum in 2006 (OECD-GSF, 2006), in many countries, learning Science and Technology is less and less attractive for young people. At the same time, the overall needs for competences in scientific and technological fields are increasing. Changing the way Science and Technology is learned is becoming of crucial importance.

Besides these general trends, French "*Ecoles d'ingénieurs*" are now compelled to define the learning outcomes of their curricula in the form of a targeted knowledge, skills and competencies framework: the national accreditation body "*Commission du titre d'ingénieur*" proposed, as a reference since 2006, a general "capacities and competencies framework"; and it has now been completed by the European Qualification Framework initiative adopted by European Parliament and Council in 2008, which is supposed to be applied from 2010 onwards.

With the support of our Board, we have decided, in *Ecole d'ingénieurs* CESI, to address these issues in an innovative way, and to face a double challenge concerning our curricula in Science: to define competency-based curricula, and to make learning more attractive by using modelling techniques and tools together with a Problem-based Learning (PBL) approach.

This year, *Ecole d'ingénieurs* CESI has in total 2715 students registered for all its curricula in engineering over the 12 centres, and near hundred teachers in Sciences. So, the new approach has to be progressive, accepted by the teachers and carefully validated before being generalized (Raine & Symons, 2005). This is why the project team has decided to start with a limited experiment involving a few teachers in Mechanics. This experiment is monitored by the Learning Environments Design Laboratory, the Educational Sciences Laboratory of the school.

To measure the effects of the new course and compare the learning outcomes with those of the traditional course, two well-known tests will be used: the Force Concept Inventory (Hestenes, Wells and Swackhamer, 1992), and the Mechanics Baseline Test (Hestenes and Wells, 1992). The FCI will be administrated in October and November 2010 to all the students in the school prior to starting the experiment. This will give a picture of the average level before any course in Mechanics at the school (students in 1st year), and after a course given in the traditional way (students in 2nd and 3rd years). The MBT will also be administrated to the students in 2nd and 3rd year. The FCI will be used again for the 1st year students after the first part of the course in Mechanics (which can be considered as a revision) to measure the gains of the experimental course and to compare them with those of traditional courses given in parallel. The MBT will also be administrated to 1st year students before and after the second part of the course with a similar intention: to measure the respective effects of traditional and experimental courses.

This presentation will focus on the methodology used to design the experimental curriculum in Mechanics and will provide some detailed examples of learning situations and problems designed in order to acquire given competencies.

Our competencies framework for sciences

Within the scope of this project, "competency" has been defined as the ability to use cognitive resources (knowledge), operative resources (skills, competencies) and monitoring indicators, in a given situation (context), to achieve specific outcomes (expressed by the progressive form of a verb, followed by a direct object) (Fig 1). Such a definition is recursive, since a competency can also use another competency as a resource, as shown by the general diagram transcribing our understanding of the competencies required by the "*Commission du titre d'ingénieur*" for sciences, our proposed competency framework for sciences (Fig. 2).

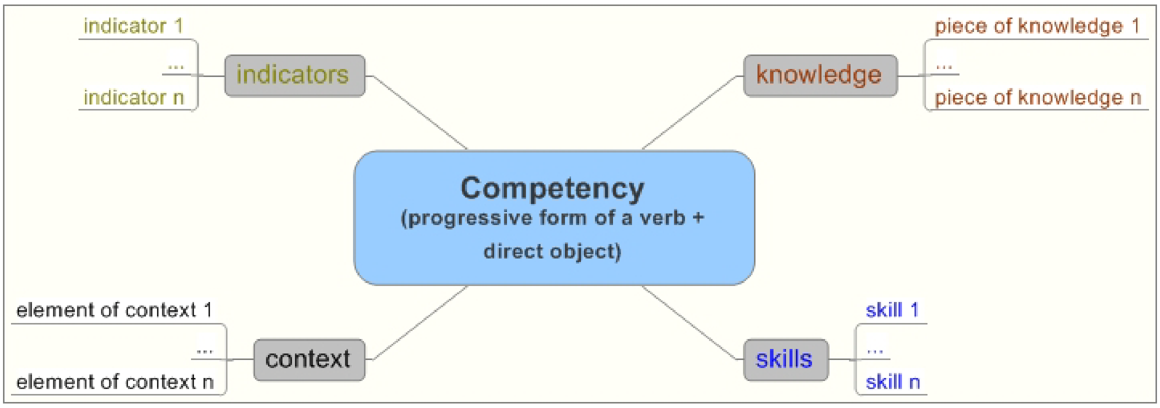

Figure 1: Definition of a competency

The core competency of our competency framework for sciences is "Mobilizing fundamental sciences resources" to help find solutions to problems in various fields of engineering. This competency describes the ability for an engineer to use scientific concepts and principles and to apply them correctly to solve specific problems. It uses 3 "companion" competencies:

- "Using a way of reasoning appropriate to the problem to resolve", because the ability to select the right way of reasoning about a specific problem facilitates the search of a solution, and we know that students frequently have "misconceptions" in physics, which need to be identified and corrected[1];
- "Using tools and procedures", because tools and in particular software tools are more and more necessary in engineering and sciences, in particular with the development of Simulation-Based Engineering Science (NSF, 2006; WTEC, 2009);
- "Collecting and interpreting data", because this ability facilitates the control of the correctness of the way of reasoning, in particular when the "functional dependency of variables" is mastered (Viennot, 1992).

[1] Many research works have been done throughout the world about these misconceptions, and it would be difficult to cite here all these works. I will just mention the work done in the USA by David Hestenes and his colleagues (Hestenes, Wells & Swackhamer, 1992; Hestenes & Wells, 1992; Horton, 2007), and in France by Laurence Viennot and her team (Viennot, 1979; 1992; Closset, 1983; 1992; Rozier, 1988), and the "Conceptual and Reasoning Difficulties in Science" website (http://www.card.unp.ac.za/home.asp) which allow researchers worldwide to share their findings in this domain.

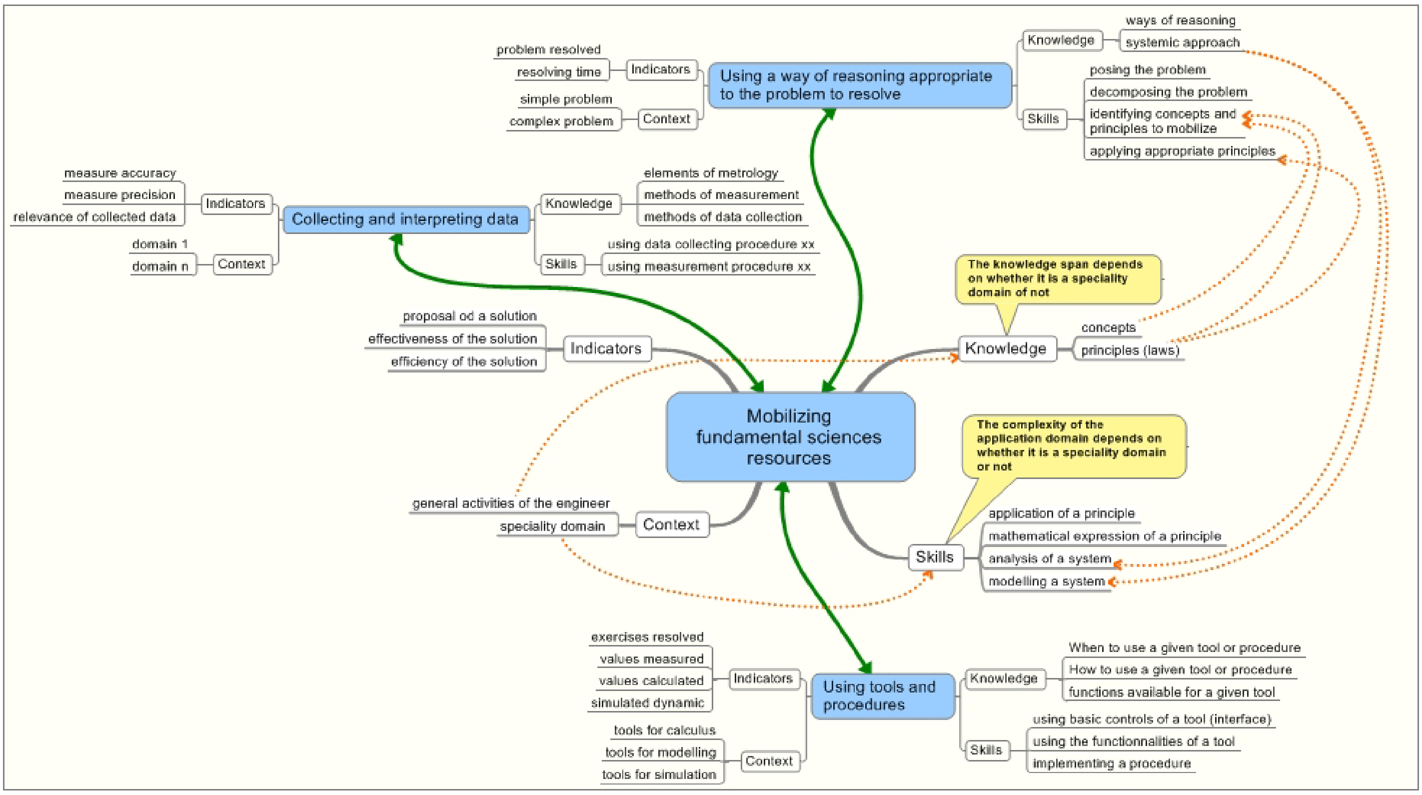

Figure 2: Our proposed competency framework for sciences

PBL as a relevant approach to acquire the required competencies

Once the competency framework has been established and agreed, the question was "which instructional approach will allow our students to acquire and develop these competencies?" Problem-Based Learning[2], which has been implemented in CESI's School of Informatics, eXia, for several years (Sandel, Allard & Maufette, 2006) appeared as a good candidate.

Our experience in another domain (Informatics) revealed that PBL develops among our students the ability to identify and formulate a problem, and to set relevant parameters for the development of a solution. This is confirmed by Savery's article as "*a critical skill developed through PBL*" (2006, p. 13). And this is precisely the main skills which are mobilized by the first "companion" competency in our competency framework, "Using a way of reasoning appropriate to the problem to resolve".

Though PBL has not been much used in physics so far, it appears as having a great potential to align "teaching" and assessment when assessment means "assessment of competencies" and not only assessment of knowledge (Raine & Symons, 2005). This means, in other terms, that PBL is a good approach to acquire competencies.

The few experiments of PBL in physics which have been recently published provide contradictory results: for Sahin & Yorek (2009), there is no significant difference in terms of "expectations" and results between students having attended a traditional elementary course in physics and those having attended a PBL session; whereas for Ali & Rubani (2009), students

[2] Many books and articles have been published on PBL since Barrows and Tamblyn's seminal book (Barrows & Tamblyn, 1980), and it is difficult to cite all these works here. A good synthesis on this instructional method is provided by Savery's article introducing the first issue of the recent journal dedicated to this approach, *The Interdisciplinary Journal of Problem-based Learning* (Savery, 2006).

having attended a PBL session show improvements in team work, presentation skills, interpersonal communication and critical thinking.

A recent meta-analysis of researches on PBL concludes that sciences, in general, are a domain where PBL has not been proven as more efficient than other instructional methods (Walker & Leary, 2009). But Jonassen & Hung (2008) point out that "all problems are not equal", and discuss the implications of such a statement for PBL. It appears, from this discussion, that efficiency of PBL is related to the problem used, and that a "good problem" should have the following characteristics:

- "*open ended, ill structured, however,*
    - *with a moderate degree of structuredness;*
- *complex, however, the degree of complexity should*
    - *be challenging and motivating, engaging students' interests;*
    - *provide opportunities for students to examine the problem from multiple perspectives or disciplines;*
    - *adapted to students' prior knowledge;*
    - *adapted to students' cognitive development and readiness;*
- *authentic*
    - *contextualized as to students' future or potential workplaces.*" (p. 16)

According to these authors, problems suitable for PBL should fall into one of the following categories: Diagnosis – Solution problems, Decision-making problems, Policy problems and Design problems (Jonassen & Hung, 2008).

The latter category, "Design problems", perfectly fits with our objectives and our competency framework, and it allows our students to learn and apply a wide range of scientific concepts and principles to solve them. So, adoption of PBL was agreed.

But according to Jonassen & Hung (2008) we need to be careful: Design problems require "*more time for scoping the problem and gathering information*", and if we want to make sure that our students have acquired the right concepts and principles (and not "alternative" conceptions or ways of reasoning, we also have to take into account one of Savery's recommendations: "*A closing analysis of what has been learned from work with the problem and a discussion of what concepts and principles have been learned are essential. Given that PBL is a very engaging, motivating and involving form of experiential learning, learners are often very close to the immediate details of the problem and the proposed solution. The purpose of the post-experience debriefing process* […] *is to consolidate the learning and ensure that the experience has been reflected upon.*" (Savery, 2006, p. 14). The importance of debriefing to consolidate learning outcomes of any experience-based learning situation is also confirmed by many research works in the field of "*Didactique professionnelle*"[3], and in particular by Pastré (2004; 2006).

An overview of the design process for the curriculum

Our competency framework for sciences and the intention to use "Design problems" to develop a Problem-Based Learning curriculum were the basic inputs to the design process for the new curriculum.

[3] This field of research has developed in France for more than 20 years to understand experience-based learning, particularly in work contexts. There are many publications in French. A good overview of this field of research is given by the following papers from Vergnaud (1992; 2004) and Pastré (2004; 2006; 2008).

The experimental curriculum should replace the traditional course, and allow the students to pass the same exams: it must be compliant with the traditional course programme, and allow learning the same concepts, the same principle, and learning when and how to apply them.

So, to be able to compare the traditional course programme and the new curriculum, we had to identify at a very detailed level the elements of the core competency acquired through the traditional course, which means to identify the abilities, the resources (knowledge, skills) mobilized and their contexts, i.e. the application fields. To achieve this, a teacher of the research group was asked to provide a detailed list of the learning objectives for the traditional course. These learning objectives were then translated into competency elements, allowing a very detailed description of the two parts of the curriculum (revision and course): each competency element is described within a context of application, with the associated concepts and principles which should be mastered, the associated tools including mathematical expressions that should be used, etc. An example is given below (Table 1)

<table>
<tr><th>Competency element</th><th>Domain of application</th><th>Concepts</th><th>Principles</th><th>Tools</th></tr>
<tr><td rowspan="3">Establishing the kinematics of oscillating systems</td><td>A system composed of a solid and a spring (no friction)</td><td>Back-moving force</td><td rowspan="2">Newton’s second law</td><td rowspan="3">Equation of oscillatory motion

Modelling / simulation tools</td></tr>
<tr><td>A system composed of a solid and a spring (with friction)</td><td>Back-moving force, Friction</td></tr>
<tr><td>Sustained oscillation</td><td>Sustained oscillation, Exciter</td><td>Fundamental mode of vibration</td></tr>
</table>

Table 1: Example of a detailed part of the competency-based description of the curriculum

In all, we determine 8 elements of the core competency which should be mastered, evidence being given through 24 fields of application during the revision part, and 6 elements of the core competency to acquire through 42 fields of application for the second part of the curriculum. The most important element of the core competency acquired during the course is “Analysing a mechanical system” which requires 20 different fields of application.

The list of these elements of the core competency was then circulated to the other teachers of the experimental group, and also to some others, for comments. The few comments provided were taken into account in the final version of the list, which will be used to design the PBL situations and to check their covering of the programme.

The second step was the design of the problems which will be used. The first problem was conceived and designed with the help of a PBL tutor from eXia, CESI School of Informatics, well-trained in the PBL approach and in Problem design, and who is himself an engineer. Then, after this first trial, a list of problems covering the curriculum has been established.

This first problem aims at giving evidences that basic concepts (such as velocity, acceleration, force, mass, weight, kinetics energy, potential energy…) and principles of Newtonian Physics are applied correctly. It covers 7 out of 8 of the core competency elements, and 20 out of 24 applications fields for the revision part of the course (power and concepts related to rotational / circular motion such as torque or momentum are not covered by this first problem). The results of the FCI test will help identify students having difficulties with these concepts and principles. The problem is introduced by a letter from a railway engineer to a friend who is physicist: “*I anticipate potential problems with our hump yard, and I fear that our new wagons rush down the hump with a final velocity much too high for our points, and end their course with too much energy for our buffers. According to what I remind from my courses in* *physics, this sort of things is calculable. We have a budget to buy new car retarders. Can you help me to dimension them?*"

The resources available to solve this problem are: a website explaining what is, and the different types of marshalling yards, including the hump yard; a video on internet showing the functioning of the hump yard; a document providing information about the hump yard, including its plan and profile (Fig. 3); the characteristics of different types of wagons; the characteristics of the bumpers and of car retarders (brakes)...

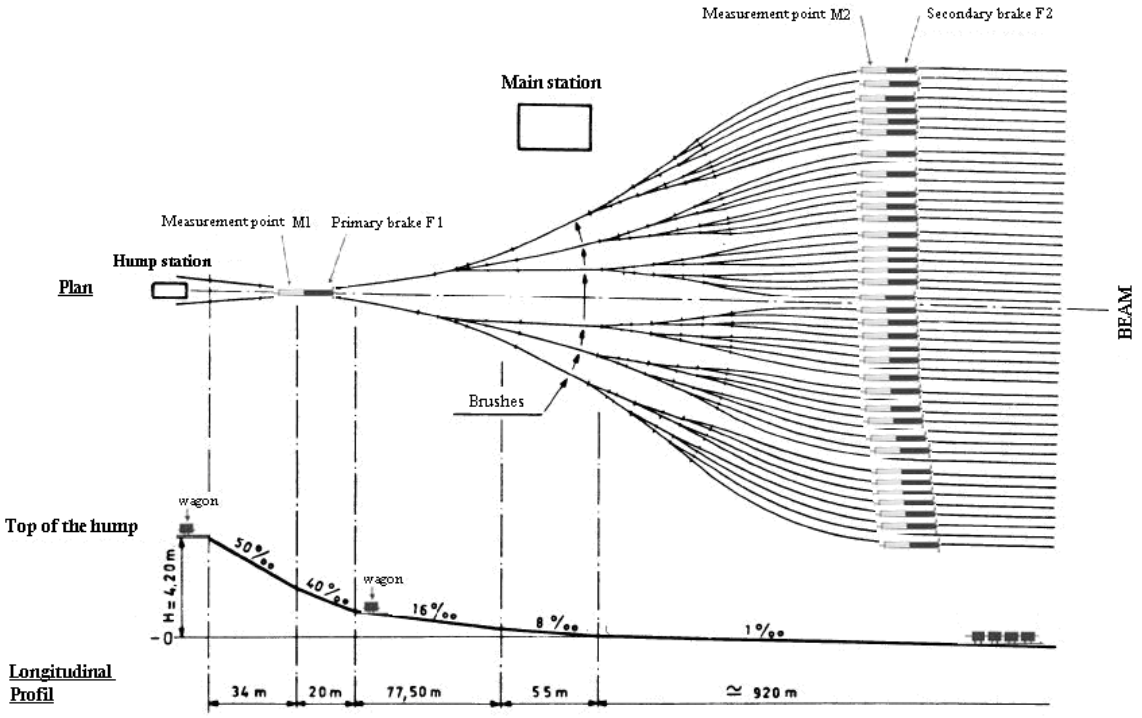

Figure 3: An example of resources for the Hump Yard Problem

For each problem, a good practice in eXia, which we decided to adopt, is that the authors develop a Tutor's Guide, which is enriched after every session in order to take into account tutors remarks, tricks and proposed improvements, and this has been done.

The second problem of the revision part intends to cover the elements of the core competency and the application fields which are not covered by the hump yard problem (power and rotational). It deals with the calculation of the efficiency of the brakes of a bicycle requested by an insurance company before an amateur cycling tour in the Alps.

The rest of the course will be replaced by 4 problems:

- Provide the characteristics of a new fastening system for a baby seat in a car resisting to a 60 mph frontal shock with a baby weighting 10kg.
- Provide the characteristics of a gear motor able to open in less than 1mn a large vertically-opening fire hall door with given characteristics.
- Calculate the length of the rotor blades for a helicopter having given characteristics.
- Explain why an amusement device crashes.

These 4 problems cover all the elements of competency and all the application fields of the second part of the course.

This is where we are at the moment of this presentation: the problems are conceived and designed, some resources need to be produced, and the problems are to be validated against the detailed list of core competency elements and application domains.

The next steps

One important step which will take place in September is training the teachers who will participate in delivering the experimental PBL curriculum to become PBL tutors. Though highly involved in the project since the beginning, when working with their colleague from eXia, they feel the necessity to attend, as observers, a PBL session in the School of Informatics, and then they asked for being trained as tutors. The main reason is that they discovered that students starting PBL are generally lacking of "*cognitive self-monitoring and self-regulation*" (Savery, 2006, p. 15), as their colleagues from eXia experienced it, and therefore students "*require significant instructional scaffolding to support the development of problem-solving skills, self-directed learning skills, and teamwork/collaboration skills to a level of self-sufficiency where the scaffolds can be removed*" (d°). This appears to be crucial for the project, especially since our students will have at the same time traditional courses in other disciplines, which is an instructional form they might prefer because they are used to it and because it requires less effort from them!

Prior to starting the experimentation of the new curriculum, as said in the introduction, all the students of the school will take the FCI test, and all the 2nd and 3rd year students will also take the MBT test. These tests have been ported onto our LMS, which is based on Moodle, and we still have to organise the test-taking in our 12 centres for October 2nd and 3rd year) and November (1st year).

And then, we will start the experimentation. Between November 2010 and February 2011, 1st year students will follow the first part of the course in Mechanics. About 100 of them will follow the new curriculum and the rest will attend the traditional course. Then, they will all take the FCI test for the second time, followed by the MBT test. Between March 2011 and June 2011, they will follow the second part of the course, with the same distribution between the experimental course and the traditional one. At the end, they will take again the MBT test.

In July 2011, we will analyse the effects of the experimental curriculum, by processing the results to the FCI and the MBT tests, and comparing them with the results obtained after the traditional course. But this is another story, which will be reported in a future presentation.

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