International Journal of Engineering Education Vol. 28, No. 4, pp. 939–947, 2012
Printed in Great Britain

0949-149X/91 $3.00+0.00

Effectiveness of Problem-Based Learning In Engineering Education: A Comparative Study on Three Levels of Knowledge Structure*

BENOÎT GALAND, MARIANE FRENAY and BENOÎT RAUCENT
Université catholique de Louvain, Place du Cardinal Mercier, 10-B1348 Louvain-la-Neuve, Belgium.
E-mail: benoit.galand@uclouvain.be

The effectiveness of problem-based learning is still a matter of debate in higher education. A previous meta-analysis introduced a distinction between three levels of knowledge structure to be assessed (understanding of concepts, understanding of principles, and application of these concepts and principles) and showed that, in medical education, problem-based learning only significantly outperformed conventional learning on the 'understanding of principles' component. The purpose of this study is to compare the understanding of concepts, understanding of principles, and application of knowledge among engineering students before and after the introduction of a problem- and project-based curriculum (PBL). To achieve this, four cohorts of students (total N = 385), two of which had followed a lecture-based curriculum and two a PBL curriculum, completed a criterion-referenced test assessing the three levels of knowledge structure. It was found that students from the PBL curriculum outperformed students from the conventional curriculum, particularly on the application of knowledge. In conclusion, these results indicate that PBL can be effective in engineering education, but bring into question the generalizability of findings from medical education to other curricula in higher education (especially when a project-based learning component is added).

Keywords: achievement; skills; learning; curriculum; innovation

1. Introduction

Instructional practices inspired by problem-based and project-based learning (PBL[1]) are being implemented more and more often in higher education throughout the world [1–3]. Within PBL environments, learning is organized around ill-defined and/or complex projects. Students are usually asked to work in teams (under the supervision of a tutor) to understand the problems and/or undertake the projects [4, 5].

1.1 The effectiveness of PBL

In spite of its growing popularity, evidence on the efficacy of PBL for improving student learning is limited. A growing body of research indicates that students on problem-based curricula report more self-directed learning and better perception of their learning environment than students following more conventional curricula [6, 7]. However, findings for achievement—which is the focus of most research—are contradictory. Some studies have reported positive results from problem-based learning, but null or negative results are widespread [3, 8, 9]. The most-frequently cited reviews found that problem-based learning had a negative effect on the acquisition of knowledge, but positive, although sometimes non-significant, effects on clinical performance [10, 11]. More recently, a meta-analytic study [12] found a negative effect of problem-based learning on Part I of the National Board of Medical Examiners (NBME) (which mainly assesses student knowledge), and positive, but non-significant effects on NBME Part II (which relies more on clinical skills). Similarly, comparing students from traditional and problem-based medical curricula, two independent groups of researchers [13, 14] found no differences in the acquisition of knowledge, but a positive effect of problem-based learning on clinical reasoning. Controlling for pre-selection, Hoffman *et al.* [15] noticed that students from a problem-based curriculum usually performed better than other first-time examinees on the United States Medical Licensing Examination (USMLE) Step 1 and Step 2. On the other hand, a review by Smits *et al.* [17] found no consistent evidence that problem-based learning was superior to other educational strategies in increasing doctors' knowledge and performance in continuing medical education. Two recent reviews still underscored the conflicting evidence about PBL effectiveness [18, 19].

These mixed results have led some reviewers to conclude that, overall, problem-based learning has no significant effect on student achievement [8, 20]. Others have argued that expecting curriculum intervention to have an effect on achievement is unrea-

---

[1] In this study, the abbreviation 'PBL' is used to designate problem- and project-based learning in higher education [16].

* Accepted 8 March 2012.

sonable in selective programmes such as medicine [21, 22]. Moreover, many criticisms have been formulated about the methodological shortcoming of the available evidence [18, 19]. But the best explanation for these contradictory findings is probably provided by a meta-analysis conducted by Dochy *et al.* [23]. They ranked the outcome measures used in evaluation studies on a continuum from knowledge acquisition (assessed by factual questions and focusing on understanding concepts), to knowledge application (assessed by complex and authentic tasks). They predicted that the positive effect of problem-based learning would be more pronounced for knowledge application, and that the negative effect would be limited to knowledge acquisition, because knowledge application is better fitted to the kind of skills that problem-based learning is supposed to foster (such as flexible knowledge, problem solving, self-directed learning, and collaborative work) [24]. The results supported their predictions, showing a robust effect in favour of problem-based learning on knowledge application, and a weak effect in favour of lecture-based learning on knowledge acquisition. A recent qualitative analysis of the results of meta-analyses on the effectiveness of problem-based learning came to similar conclusions [25]. Gijbels, Dochy, Van den Bossche and Segers [26] went a step further by distinguishing three levels of knowledge structure to be assessed: the understanding of concepts; the understanding of principles that link concepts; and the linking of concepts and principles to conditions and procedures for application. The results of their meta-analysis showed that problem-based learning only significantly outperformed conventional learning for the understanding-of-principles component.

However, available evidence about the effectiveness of problem-based learning in higher education is mainly limited to the education of health professionals [27]. Walker and Leary [28] tried to find evidence in other disciplines, but had to rely mainly on unpublished studies or on studies conducted at secondary school. They reported similar, very small, unweighted mean effect sizes in medical and engineering education. Within specific courses, the burgeoning research on the effectiveness of PBL outside medical education (e.g. chemistry, physics, business, teaching) provides inconsistent findings regarding the level of knowledge structure fostered by PBL [16, 29–31]. With regard to project-based learning, very few systematic reviews have been published, with the exception of science education at the primary and secondary level, where the positive effects seem to be consistent [32–34]. The generalizability of these effects in other disciplines and in higher education is still open to question, especially at the level of a whole curriculum.

There are a large number of variants of problem- and project-based learning (PBL), but studies generally provide poor descriptions of the curricula being compared and no indications of the quality of implementation [17, 18]. Variations in effectiveness could thus originate in variations in instructional design or implementation [35]. In addition, it is difficult to relate students' outcomes to changes in specific curriculum features or instructional practices, and to know how PBL affects student learning [36, 37]. So despite the volume of literature on PBL, the effects of PBL on the quality of learning in different contexts and in different instructional designs are insufficiently documented [9, 38].

The aim of our study was to use the three levels of knowledge structure identified by Gijbels and colleagues [26] in order to assess the mid-term effects of a shift from a conventional 'lecture-based' curriculum to a problem- and project-based curriculum on student in engineering education.

1.2 Description of the PBL curriculum

The Louvain School of Engineering has approximately 1200 students on its 5-year programme. A typical first-year cohort consists of 350 to 380 students. After considerable debate, the School of Engineering decided in 2000—by a very small majority—to shift the curriculum of the first two years of its undergraduate programme from a traditional lecture-based curriculum to a problem- and project-based learning curriculum [39]. The major reasons for the change were low student motivation, relatively shallow mastery of course material, low retention rate, little demonstration of higher-order skills, and too little initiative or autonomy. A significant portion of the teaching staff was less than happy with the students' achievements: for all the effort expended (both by teachers and by students), the level of competence achieved was perceived as disappointing, particularly in the first two years of the course [40]. The objectives of the PBL curriculum were mostly intended to enhance deep and meaningful learning, to promote high-level capabilities, to develop student motivation and autonomy, and to promote teamwork [41].

The PBL curriculum relies on active, self-directed, self-assessed, small groups, using partially tutored project- and problem-based learning in all courses. Problems and projects were designed to contribute to the acquisition of non-technical skills and competences. Long-term projects are used mostly to develop inter- and trans-disciplinary learning, while one-week problems are generally restricted to a single discipline (mathematics, physics, etc.). The idea was that these shorter problems allow students to explore disciplinary topics in a more controlled way than the longer projects, thereby ensuring that essential topics are fully covered [40]. On the other hand, the projects are intended to promote both students' autonomy and transferable group skills; students should develop the ability to define for themselves, in teams, what to learn and how to reach the goal.

A year's study is divided into three 11-week trimesters, each covering ten 1-week problems and one term-long project. A typical week contains 16 hours of scheduled contact hours (about 6 hours of lectures, 8 hours of supervised problem group work and 2 hours of supervised project group work), compared with 22 hours in the previous curriculum (including 12 hours of lecture). The groups (6 to 8 students) are constituted randomly at the beginning of each trimester. Three groups work under the supervision of a tutor (one for each discipline). The tutors can be faculty staff or senior students. All of them have been trained and are coached by senior tutors. For a more detailed description of the two curricula, see [41, 42].

Survey data from teachers and students support the idea that the introduction of the PBL curriculum was associated with real changes in instructional practices: more coordination between teachers from different disciplines, increased teacher engagement in staff development, more coaching of the students, more contextualization of teaching; but also an increased workload for students and less coherence in the assessment system [7, 43].

1.3 Aim of the study and hypotheses

The implementation of this PBL curriculum provided an opportunity to assess the impact of two years of study in a PBL environment on student achievement in engineering education [44], and to examine the generalizability of findings in medical education about PBL effectiveness [23]. We wanted to use the three levels of knowledge structure proposed by Gijbels and colleagues [26] to analyse the performance of four cohorts of students (the last two to follow the lecture-based curriculum and the first two to follow the PBL curriculum) on a test composed of three different tasks.

Dochy and colleagues [23] found that the negative effect of PBL on student knowledge acquisition was mainly evident among first- and second-year students (like the ones in the present study) and not among more advanced students. On this basis, we expected a small difference in favour of students who had followed the lecture-based curriculum on understanding of concepts (knowledge acquisition). Dochy and colleagues [23] also found that the positive effects of PBL on knowledge application were less pronounced for 'historical' studies (like the present one) than for 'elective tracks' or 'between institutes' studies (no randomized studies were reported). So we expected a small difference in favour of students from the PBL curriculum on understanding of principles and on application of concepts and principles (knowledge application).

Like many problem-based curricula in engineering, the PBL curriculum investigated in this study emphasized problem solving—not problem explanation or understanding—and included project work. Therefore, we expected the effect of PBL to be more pronounced at the application level than at the principles level, even though this contradicts results in medical education [26]. Finally, given that the transition from lecture-based to problem-based curriculum was gradual (some teachers started using the PBL approach a year before the decision to shift all the curriculum, others took another year after the curriculum shift to modify their courses), we expected any differences between Cohorts 1 and 4 to be more pronounced than those between Cohorts 2 and 3.

We also wanted to check whether the effects of the curriculum change were similar for students at various levels of achievement [2]. Previous research has paid little attention to this question, but some researchers have argued that PBL is especially well suited to boosting the achievement of weaker students, while others have claimed that PBL is particularly beneficial for high-achieving students [27]. Given the paucity of results on this question, no clear hypotheses were drawn up.

2. Method

2.1 Sample and procedure

Over a period of four years, engineering students were asked to complete a test (see below) at the beginning of their third year of study (i.e. after the successful completion of their first two years). Participation was voluntary and confidential, and the students' consent was obtained. Students were informed in advance, by the dean of the School of Engineering, of the aims and procedure of the study. The test was administered collectively; it took place during regular lecture time and lasted 90 minutes. There was a time limit for each task within the test. Cohorts 1 and 2 had followed the lecture-based curriculum and Cohorts 3 and 4 the PBL curriculum. The four test sessions were conducted by the research team. The content of the test was kept confidential, and the students had to return all the test material. The procedure was explained to them and they were asked not to talk about the content of the test.

Altogether, 397 students completed the test (mean age = 20 years; 86% male), 66 in 2000, 164 in 2001, 79 in 2002, and 88 in 2003. The participation rate was 34% in 2000, 65% in 2001, 40% in 2002, and 42% in 2003. There were no significant differences in age or gender composition between the cohorts. Students from the lecture-based curriculum got higher grade-point averages (GPAs) than students from the PBL curriculum in their second years, but GPAs at the end of the third year were similar. The admission criteria for engineering remained the same during the four years. Owing to missing data, 12 students were deleted from the analyses. The final sample was thus composed of 385 students.

2.2 *Measures*

Focusing on ecological validity, the research team collaborated with teachers from the School of Engineering (some of whom supported PBL and others who were opposed to it) to develop a criterion-referenced test. The test was designed to assess the knowledge and skills that students should have mastered by the end of two years of studying engineering (whatever kind of instructional approach they had experienced). The test content was checked by the teachers to ensure that it was taught extensively in both curricula. It was reviewed by experts in learning and test development, and pre-tested on graduate students to ensure clarity of instructions and duration of administration.

The final version of the test was composed of three written tasks: (1) defining scientific concepts and producing several size estimates; (2) solving a formal mathematics problem using differential equations; and (3) solving a contextualized problem related to the functioning of an electro-mechanical system. These tasks could be related to the three levels of knowledge structure identified by Gijbels and colleagues [26, Table 2]: the first task is mainly concerned with the understanding of concepts (e.g. generate examples), the second is focused on the understanding of principles (e.g. generate solutions), and the third covers application of concepts and principles in specific conditions (e.g. generate a procedure). The tasks are presented in the Appendix.

To avoid biases, all the papers were corrected together at the end of the fourth year of administration, by raters who did not know which cohort the students were in. Under the supervision of the research team, a model of the expected answers was developed by a team of teachers and a detailed list of success criteria for each task was derived from this model.[2] Answers were then assessed on these criteria by two independent raters, teaching at the School of Engineering. Each task was corrected by different raters. A mean score of all criteria was computed separately for each task.

Theoretical knowledge (understanding of concepts). The definitions, theoretical explanations and approximations provided by students in the first task were assessed on 30 criteria (e.g. elements of the concept, units of measurement) (inter-rater reliability = 0.80; Cronbach's alpha = 0.78).

Computation (understanding of principles). The coefficients and exponentials included in the equations, the solving of the equations, and the calculated values provided by the students in the second task were assessed on 15 criteria (e.g. B increase then decrease; correct matrix writing) (inter-rater reliability = 0.94; Cronbach's alpha = 0.82).

Problem solving (application of knowledge). The identification of key elements of the problem, the justifications, and the estimates provided by students in the third task were assessed on 12 criteria (e.g. V_0 proportional to weight; A = 5 volts/$V_{\text{threshold}}$) (inter-rater reliability = 0.85; Cronbach's alpha = 0.79).

Given the high inter-rater reliability and the good internal consistency of the scores, the mean score of the two raters was used for each task in the subsequent analyses. All scores were standardized.

3. Results

A one-way ANOVA with Cohort as the independent variable was performed on the theoretical knowledge, computation and problem-solving scores.[3] The results are presented in Table 1, and show a significant effect of Cohort on each score. Post-hoc Tukey tests indicate that:

- the theoretical knowledge score was significantly lower for Cohort 1 than for Cohort 4;
- Cohort 1 had lower average computation scores than the other three cohorts;
- Cohorts 3 and 4 had higher problem-solving scores than Cohorts 1 and 2.

To check whether the effects of PBL were the same at each level of academic achievement, or if aptitude/treatment interactions existed, the students were divided into two groups based on their second-year GPAs (over 70 % = high; between 60% and 70% = low; students with GPAs below 60% failed the year and had to repeat it). The analyses reported above were repeated with Group as a second independent variable. The results indicate that, as expected, students in the high group per-

---

[2] The complete list of criteria is available from the first author.

[3] Normality assumptions were checked and supported, except the homogeneity of variance for problem-solving (PBL cohorts had higher variance). As the Kruskal–Wallis test displayed similar results to the ANOVA, we choose to keep the same presentation for the three tasks.

Table 1. Comparison of means and standard deviations for the three tasks by curriculum (lecture-based: cohorts 1–2; problem-based: cohorts 3–4)

		Theoretical knowledge		**Computation**		**Problem solving**	
Task curriculum	***n***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Lecture-based							
Cohort 1	62	-0.23^{a}	*1.05*	-0.73^{a}	*0.63*	-0.60^{a}	*0.52*
Cohort 2	163	–0.05	*0.95*	0.16^{b}	*0.98*	-0.31^{a}	*0.78*
Problem-based							
Cohort 3	77	0.08	*1.09*	0.01^{b}	*0.90*	0.45^{b}	*1.09*
Cohort 4	83	0.19^{b}	*0.94*	0.22^{b}	*1.11*	0.64^{b}	*1.05*
F		2.33		15.16		38.35	
p		0.07		0.00		0.00	
Eta-square		0.02		0.11		0.23	

Note. All measures are standardized (Mean = 0; Standard deviation = 1).
Means with different letters differ at $p < 0.05$.

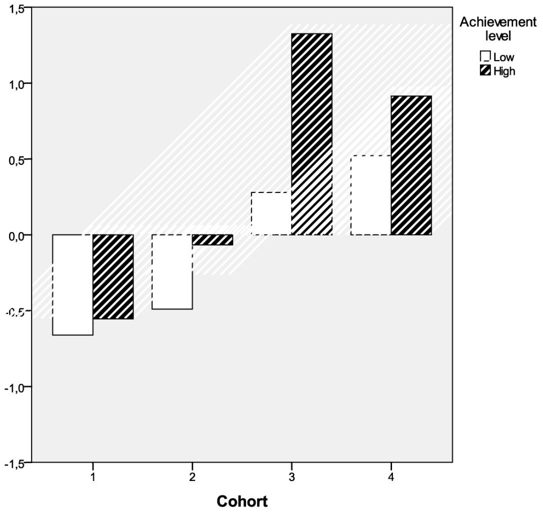

Fig. 1. Mean problem-solving score by cohort and achievement level.

formed better on the test than students in the low group, but the interaction between Group and Cohort was only significant for the problem-solving task (F(3380) = 2.86; p < 0.05). Decomposition of this interaction indicated that the difference between Cohorts 1 & 2 and Cohorts 3 & 4 was larger for student with high GPAs than for students with low GPAs (see Fig. 1). The other effects reported for the analysis by Cohort were not qualified by any interaction with Group (p > 0.10), suggesting that they were similar across achievement levels.

4. Discussion

The aim of this study was to assess the impact of two years of study in a PBL environment on engineering students' knowledge acquisition and skills development. The performance of student cohorts before and after the introduction of the PBL curriculum was compared on three different tasks. Results indicated several differences in favour of students from the PBL curriculum and no differences in favour of students from the lecture-based curriculum.

4.1 Cohorts comparison

Contrary to our expectations, we did not find any negative effects of PBL, even in the task assessing theoretical knowledge (concept understanding). Indeed, one of the PBL cohorts slightly outperformed one of the lecture-based learning (LBL) cohorts on this task. A large positive effect of PBL was found on problem-solving (application of knowledge), the two LBL cohorts scoring considerably lower than the two PBL cohorts. This difference between curricula accounted for about 23% of the variance in problem solving performance, corresponding to an effect-size of about 1.10 standard deviations. This effect is consistent with the characteristics of the PBL curriculum and with our expectations.

The pattern of means for theoretical knowledge and problem solving scores are consistent with improved performance following the gradual implementation of a PBL curriculum. Even the results for the computation task, which at a first glance may seem inconclusive in terms of differences between LBL and PBL (only the first cohort was significantly different from the other three), may be explained by this gradual implementation. Although the PBL curriculum did not start until 2002 (Cohort 3), mathematics teachers had started using problem-based learning in their courses in 2001 (Cohort 2). This may then explain why a difference on the computation score only appears between Cohort 1 and the other cohorts. The remainder of our results can be related to the shift to problem solving following the introduction of PBL at the programme level.

The results of this study are consistent with those of Dochy and colleagues [23] who showed that—in quasi-experimental studies—the impact of PBL is stronger on knowledge application than on knowledge acquisition. However, unlike the findings for medical education [26], the positive effects in engineering are more pronounced for application than for understanding of principles. At the same time, the results of the PBL curriculum in engineering seem to be more uniformly positive than those observed in medical education [8]. It is hard to say if these differences are due to the field (i.e. medicine vs. engineering) or to the specific combination of problem- and project-based learning used in the programmes evaluated (see below).

The results of this study contradict the claim made by some researchers that improvement in student knowledge and skills following curriculum intervention is an unreasonable expectation in selective programmes [21, 22]. In French-speaking Belgium, engineering education is at least as selective as medical education, and yet clear positive effects of a curriculum change were found. Moreover, our results suggest that both low-achieving and high-achieving students benefited from this change, even if the high-achievers benefited more.

4.2 Limitations

However, the value of these results is limited by the fact that the students were not randomly assigned to the two curricula. Consequently, even if cohorts did not differ on the control variables investigated, the design of our study did not allow us to fully control for selection or history bias. Randomized controlled trials remain extremely rare in this field of research and raise specific problems [19]. ‘Elective tracks’ or ‘between institute’ studies could provide methodologically sounder and stronger results [23]. However a previous study [45] found that students who selected PBL curricula differed from students who selected lecture-based curricula on several cognitive and non-cognitive entry characteristics. This suggests that ‘historical’ studies with no change in the admission process and quick curriculum change—like the one presented in this paper—may be a good way of reducing differences in entry characteristics [46]. It should be noted also that, contrary to most similar studies in medical education [18], in the present study raters were blind to the curriculum followed by the students.

Finally, the pattern of our results, showing mainly an advantage for PBL students on problem-solving—precisely the kind of skills practised more intensively in the PBL curriculum—and no differences in theoretical knowledge and computation—which were already stressed in the traditional curriculum, support the idea of an effect of the PBL curriculum rather than a change in cohorts composition. Yet this conclusion is limited to students who volunteer to participate in the study. Even if students with various levels of GPAs participated in each cohort, it could be that non-participant students differ from participants on unobserved characteristics, making the results irrelevant to them.

As our results do not rely on standardized achievement tests, they could suffer from inflated measurement error, but they also avoid the ceiling effect that can appear on these tests with a highly selected population [47]. Our test covered only a limited range of topics, but mirrors the three levels of knowledge structure described by Gijbels and colleagues [26]. The use of an outcome measure designed locally in collaboration with teachers could be suspected of favouring PBL students. However it can be argued that our measure in fact favoured the conventional curriculum: in addition to the precautions described in the method section, our assessment measure was mainly classical, and did not capture the specific learning goals of PBL (transfer, information search, critical thinking, teamwork, etc.) very well [47]. The alignment of assessment tools with learning goals and instructional approaches is certainly a challenge for further research [2, 26].

This study is limited to a comparison between a lecture-based and a PBL curriculum. It does not tell us whether other curriculum changes could produce similar or better effects, with less effort, time or energy [48, 49]. A recent review [19] suggested that PBL could be more effective in shorter interventions within a traditional curriculum than at the whole curriculum level. Finally, as we said before, the PBL curriculum evaluated in this study is a unique combination of problem- and project-based learning fitted to the needs of engineering education [42]. These two instructional approaches share numerous similarities: use of problem, active construction of knowledge, situated learning, collaboration, cognitive tools, and teachers as facilitators [33]. Also, some distinctive features of project-based learning in compulsory education—like pupil participation in the definition of the project [3] or a focus on inquiry [2]—do not apply to the assigned and production-oriented projects of this PBL curriculum. However, this curriculum may, for example, include more scaffolding and direct instruction than typical problem-based learning curricula. Further studies are needed to assess whether and how such an approach has specific effects on student learning compared to a ‘pure’ problem-based curriculum [50]. More globally, few studies have compared the effectiveness of various ‘student-centered’ instructional approaches.

5. Conclusions

The results of the present study suggest that the introduction of a curriculum inspired by problem- and project-based learning had no negative effects on engineering students' knowledge and skill development. On the contrary, they suggest that students following this PBL curriculum, whatever their previous level of achievement, developed new skills compared with students following the previous traditional curriculum. In other words, this study shows that curriculum changes can foster the development of some application skills among engineering students, without deleterious effect on other forms of learning (understanding of concepts and principles), and that PBL can provide a framework for designing such successful changes. At the same time, the results suggest that we have to be very careful in generalizing results about PBL effectiveness from medical education to other contexts [9].

Acknowledgements—This research was supported by a grant from the Louvain Foundation. The authors thank Etienne Bourgeois, Marie Bronchart, Fabienne de Voghel, Auguste Laloux, Elie Milgrom, Cécile Vander Borght and Pascale Wouters for their support in this project. They also thank teachers from the School of Engineering who devoted time and energy in the development and rating of the test and the anonymous reviewers for their helpful comments.

References

1. D. H. Evensen and C. E. Hmelo, *Problem-Based Learning: A Research Perspective* on *Learning Interactions*, Lawrence Erlbaum, Mahwah, NJ, 2000.
2. C. Hmelo-Silver, Problem-based learning: What and how do students learn? *Educational Psychology Review,* **16**, 2004, pp. 235–266.
3. S. M. Loyens, P. A. Kirschner and F. Paas, Problem-based learning. In K. Harris, S. Graham, T. Urdan, A. Bus, S. Major and L. Swanson (eds), *APA Educational Psychology Handbook, Vol. 3: Application to learning and teaching*, American Psychological Association, Washington DC, 2011, pp. 403–425.
4. E. De Graaff and A. Kolmos, Characteristics of Problem-Based Learning. *International Journal of Engineering Education,* **19**, 2003, pp. 657–662.
5. M. Frenay and B. Galand, Les dispositifs d'apprentissage par problèmes dans l'enseignement supérieur [Problem-based learning curricula in Higher Education]. In V. Dupriez and G. Chapelle (eds), *Enseigner*, Presses Universitaires de France, Paris, 2007, pp. 117–127.
6. F. Dochy, M. Segers, P. van den Bossche and K. Struyven, Students' perceptions of a problem-based learning environment, *Learning Environments Research,* **8**, 2005, pp. 41–66.
7. B. Galand, B. Raucent and M. Frenay, Engineering students' self-regulation, study strategies, and motivational beliefs in traditional and problem-based curricula, *International Journal of Engineering Education,* **26**, 2010, pp. 523–534.
8. J. A. Colliver, Effectiveness of problem-based learning curricula: Research and theory. *Academic Medicine,* **75**, 2000, pp. 259–266.
9. M. Newman, *A Pilot Systematic Review and Meta-Analysis on the Effectiveness of Problem-Based Learning*, Learning and Teaching Support Network—01, Medicine, Dentistry and Veterinary Medicine, Newcastle, UK, 2003.
10. M. A. Albanese and S. Mitchell, Problem-based learning: a review of literature on its outcomes and implementation issues, *Academic Medicine,* **68**, 1993, pp. 52–81.
11. D. T. Vernon and R. L. Blake, Does problem-based learning work? A meta-analysis of evaluative research, *Academic Medicine,* **68**, 1993, pp. 550–563.
12. H. A. Kalaian, P. B. Mullan and R. M. Kasim, What can studies of problem-based learning tell us? Synthesizing and modeling PBL effects on National Board of Medical Examination performance: Hierarchical linear modeling meta-analytic approach, *Advances in Health Sciences Education,* **4**, 1999, pp. 209–221.
13. K. Lonka, J. Nieminen, F. Sjoblom and P. Scheinin, Effects of problem-based learning in medicine. Paper presented at the *11th biennial conference of the European Association for Research on Learning and Instruction*, Nicosia, Cyprus, 2005, August.
14. L. H. Distlehorst, E.Dawson, R. S. Robbs and H. S.Barrows, Problem-based learning outcomes: The glass half-full, *Academic Medicine,* **80**, 2005, pp. 294–299.
15. K. Hoffman, M. Hosokawa, R. Blake, L. Headrick and G. Johnson, Problem-based learning outcomes: Ten years of experience at the University of Missouri-Columbia School of Medicine, *Academic Medicine,* **81**, 2006, pp. 617–625.
16. D. Williams, J. Woodward, S. Symons and D. Davies, A tiny adventure: the introduction of problem based learning in an undergraduate chemistry course, *Chemistry Education Research and Practice,* **11**(1), 2010, pp. 33–42.
17. P. B. A. Smits, J. H. A. M. Verbeek and C. D. de Buisonjé, Problem based learning in continuing medical education: A review of controlled evaluation studies, *British Medical Journal,* **324**, 2002, pp. 153–156.
18. L. Hartling, C. Spooner, L. Tjosvold and A. Oswald, Problem-based learning in pre-clinical medical education: 22 years of outcome research, *Medical Teacher,* **32** (1), 2010, pp. 28–35.
19. I. Polyzois, N. Claffey and M. Mattheos, Problem-based learning in academic health education. A systematic literature review, *European Journal of Dental Education,* **14**(1), 2010, pp. 55–64.
20. P. M. Finucane, S. M. Johnson and D. J. Prideaux, Problem-based learning: Its rationale and efficacy, *Medical Journal of Australia,* **168**, 1998, pp. 445–448.
21. M. A. Albanese, Problem-based learning: Why curricula are likely to show little effect on knowledge and clinical skills, *Medical Education,* **34**, 2000, pp. 729–738.
22. G. R. Norman and H. G. Schmidt, Effectiveness of problem-based learning curricula: Theory, practice and paper darts, *Medical Education,* **34**, 2000, pp. 721–728.
23. F. Dochy, M. Segers, P. Van den Bossche and D. Gijbels, Effects of problem-based learning: a meta-analysis, *Learning and Instruction,* **13**(5), 2003, pp. 533.
24. A. C. Kelson and L. H. Distlehorst, Group in problem-based learning (PBL): Essential elements in theory and practice. In D. H. Evensen and C. E. Hmelo (eds), *Problem-Based Learning: A Research Perspective on Learning Interactions*, Lawrence Erlbaum, Mahwah, NJ, 2000, pp. 167–184.
25. J. Strobel and A. van Barneveld, When is PBL more effective? A meta-synthesis of meta-analyses. Comparing PBL to conventional classrooms, *The Interdisciplinary Journal of Problem-based Learning,* **3**(1), 2009, pp. 44–58.
26. D. Gijbels, F. Dochy, P. van den Bossche and M. Segers, Effects of problem-based learning: A meta-analysis from the angle of assessment. *Review of Educational Research,* **75**(1), 2005, pp. 27–61.
27. J. R. Mergendoller, N. L. Maxwell and Y. Bellisimo, The effectiveness of problem-based instruction: a comparative study of instructional methods and student characteristics, *The Interdisciplinary Journal of Problem-Based Learning,* **1**, 2006, pp. 49–69.
28. A. Walker and H. Leary, A problem based learning meta analysis: Differences across problem types, implementation types, disciplines, and assessment levels, *The Interdisciplinary Journal of Problem-Based Learning,* **3**(1), 2009, pp. 12–43.
29. N. Capon and D. Kuhn, What's so good about problem-based learning? *Cognition and Instruction,* **22**, 2004, pp. 61–79.

30. M. Sahin, Effects of problem-based learning on university students' epistemological beliefs about physics and physics learning and conceptual understanding of Newtonian mechanics, *Journal of Science Education and Technology,* **19**(3), 2010, pp. 266–275.
31. S. Sendag and H.F. Odabasi, Effects of an online problem based learning course on content knowledge acquisition and critical thinking skills, *Computers & Education,* **53**(1), 2009, pp. 132–141.
32. M. Barak and Y. J.Dori, Enhancing undergraduate students' chemistry understanding through project-based learning in an IT environment, *Science Education,* **89**, 2005, pp. 117–139.
33. J. S. Krajcik and P. C. Blumenfeld, Project-based learning. In K. Sawyer (ed.), *The Cambridge Handbook of the Learning Sciences*, Cambridge University Press, UK, 2006, pp. 317–333.
34. J. W. Thomas, *A Review of Research on Project-Based Learning*, The Autodesk Foundation, San Rafael, CA, 2000.
35. D. H. J. M. Dolmans, W. De Grave, I. H. A. Wolfhagen and C. P. M. Van der Vleuten, Problem-based learning: Future challenges for educational practice and research, *Medical Education,* **39**, 2005, pp. 732–741.
36. P. Blumberg, Evaluating the evidence that problem-based learners are self-directed learners: A review of the literature. In D. H. Evensen and C. E. Hmelo (eds), *Problem-Based Learning: A Research Perspective on Learning Interactions,* Lawrence Erlbaum, Mahwah, NJ, 2000, pp. 199–226
37. J. Nijhuis, M. Segers and W. Gijselaers, Influence of redesigning a learning environment on student perceptions and learning strategies, *Learning Environments Research,* **8**, 2005, pp. 67–93.
38. C. E. Hmelo-Silver, R. G. Duncan and C. A. Chinn, Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark, *Educational Psychologist,* **42**, 2007, pp. 99–107.
39. E. Milgrom and B. Raucent, La réfrome de programme Candis 2000 [The 'Candis 2000' programme reform]. In B. Galand and M. Frenay (eds), *L'approche par problèmes et par projets dans l'enseignement supérieur : Impact, enjeux et défis*, Presses Universitaires de Louvain, Louvain-la-Neuve, 2005, pp. 15–42.
40. E. Aguirre, C. Jacqmot, E. Milgrom, B. Raucent, A. Soucisse and C. Trullemans, Meeting the needs of our stakeholders: engineering a new engineering curriculum at UCLouvain, *Proceedings of the SEFI Annual Conference 2001*, Copenhagen, pp. 1–5.
41. M. Frenay, B. Galand, E. Milgrom and B. Raucent, Project- and problem-based learning in the engineering curriculum at the University of Louvain. In E. De Graaff and A. Kolmos (eds), *Management of Change: Implementation of Problem-Based and Project-Based Learning in Engineering,* Sense Publisher, Rotterdam, 2007, pp. 93–108.
42. B. Raucent, J.-M. Braibant, M.-N. de Theux, C. Jacqmot, E. Milgrom, C. Vander Borght, *et al.*, Devenir ingénieur par apprentissage actif : compte-rendu d'innovation [Becoming engineer by active learning: Report on an innovation], *Didaskalia,* **24**, 2004, pp. 81–101.
43. B. Galand and M. Frenay (eds), *L'approche par problèmes et par projets dans l'enseignement supérieur : Impact, enjeux et défis* [Problem and project based learning in Higher Education: Impact, issues, and challenges], Presses Universitaires de Louvain, Louvain-la-Neuve, 2005.
44. C. Vander Borght, C. Jacqmot, A. Laloux, E. Milgrom, B. Raucent, E. Bourgeois, B. Galand and M. Frenay, Evaluating a problem/project based learning programme at the engineering faculty of UCL, *Proceedings of 'PBL2002: A Pathway To Better Learning', International Conference in Higher Education,* Institute for Transforming Undergraduate Education at the University of Delaware, Baltimore, USA, 2002, 37.
45. L. D. Cariaga-Lo, B. F. Richards, M. A. Hollingsworth and D. L. Camp, Non-cognitive characteristics of medical students: Entry to problem-based and lecture-based curricula, *Medical Education,* **30**, 1996, pp. 179–186.
46. J. Cohen-Schotanus, A. M.Muijtjens, J. Schönrock-Adema, J. Geertsma and C. P. M. van der Vleuten, Effects of conventional and problem-based learning on clinical and general competencies and career development, *Medical Education,* **42**, 2008, pp. 256–265.
47. H. G. Schmidt, S. M. Loyens, T. van Gog and F. Paas, Problem-based learning is compatible with human cognitive architecture: Commentary on Kirschner, Seweller, and Clark (2006), *Educational Psychologist,* **42**, 2007, pp. 91–97.
48. P. A. Kirschner, J. Sweller and R. E. Clark, Why minimal guidance does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching, *Educational Psychologist,* **41**, 2006, pp. 75–86.
49. A. Petrosino, T. Martin and V. Svihla (eds), Developing student expertise and community: Lessons from how people learn, *New Directions for Teaching and Learning, No. 108,* Jossey-Bass, 2007.
50. B. J. S. Barron, D. L. Schwartz, N. J.Vye, M. Allison, A. Petrosino, L. Zech *et al.*, Doing with understanding: Lessons from research on problem- and project-based learning, *The Journal of the Learning Sciences,* **7**(3/4), 1998, pp. 271–311.

Appendix

Task 1—Theoretical knowledge (concepts)

1. Define (as precisely as you can):
   - The first law of thermodynamics
   - An eigenvector
   - A magnetic field
2. Restate the first law of thermodynamics in your own terms and illustrate its application.
3. Give and justify an approximation of the following quantities:
   - torque applied by a cyclist to the crank gear
   - power developed by a cyclist
   - work done by a cyclist after one hour's cycling

Task 2—Computation (principles)

A chemical reaction proceeds as follow:

$A \rightarrow B \rightarrow C$

A, B and C masses are time dependent and are noted $a(t)$, $b(t)$ and $c(t)$. Differential equations describe their evolution:

$$\mathrm{d}a/\mathrm{d}t = -k_1\, a$$
$$\mathrm{d}b/\mathrm{d}t = k_1\, a - k_2\, b$$
$$\mathrm{d}c/\mathrm{d}t = k_2\, b.$$

The boundary conditions are: $a(0) = M$, $b(0) = c(0) = 0$ and it is assumed that: $k_2 > k_1 > 0$.

1. Prove that there is conservation of the total mass $m(t)$.
2. Give an approximation of the time evolution of $a(t)$, $b(t)$ and $c(t)$.
3. Give the solutions $a(t)$, $b(t)$ and $c(t)$.
4. When is mass $b(t)$ maximum?

Task 3—Problem solving (application)

Figure A.1 shows a device that distinguishes 2€ coins from other coins:

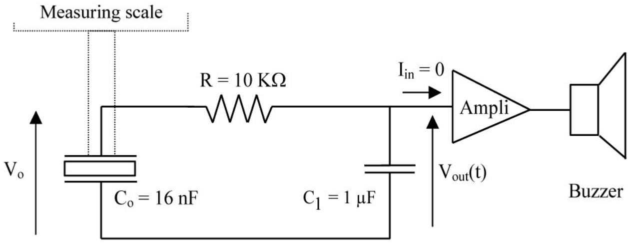

Fig. A.1. Device for distinguishing coins.

Explain, in your own words, what happens when a 2€ coin is placed on the measuring scale. Give a simplified electrical schematic of the system.

Give and justify a choice for the value of V_{out} and for the amplification factor needed to separate 2€ coins from other ones.

Estimate the time needed for detection. Give the main steps of your calculation.

Benoît Galand is a professor at the department of Psychology and Education of the Université catholique de Louvain and received his Ph.D. in psychology in 2001. His research interests focus on the effects of instructional practices on student motivation, emotional adjustment, learning and social behaviour. He is a member of the Interdisciplinary Research Group on Socialization, Education and Training (GIRSEF). He lectures in educational psychology, pedagogy and research methodology for graduate and undergraduate students.

Mariane Frenay is a professor at the Université catholique de Louvain, Belgium (Faculty of Psychology and Education) and received her Ph.D. in Instructional Psychology in 1994. She is an active researcher in the field of higher education teaching and learning and faculty development, and since 2001, she has been part of the UNESCO Chair of university teaching and learning of her university. She is currently the president of the European Network for research on innovation in higher education (RERIES). She has been teaching for several years in the Masters and the Doctoral programmes in Psychology and in Education.

Benoit Raucent obtained his degree in mechanical engineering from the Université catholique de Louvain (Belgium) in 1984, a DEA in robotics and automation from the Université des Sciences et Techniques du Languedoc (Montpellier-France) in 1985 and a Ph.D. degree from UCL in 199. Since 1985, he has been an associate professor at the department of Mechanical Engineering at UCL and Professor since 2000. He lectures in mechanical drawing and mechanical design for undergraduate students.