Problem-Based Learning in Aerospace Engineering Education

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Abstract

Problem-based learning is now a widespread teaching method in disciplines where students must learn to apply knowledge, not just acquire it. In the undergraduate curriculum in Aeronautics and Astronautics at MIT, problem-based learning and design-build experiences are integrated throughout the program. In an early freshman-year experience, *Introduction to Aerospace and Design*, students design, build, and fly radio-controlled lighter-than-air (LTA) vehicles. In the sophomore-year *Unified Engineering* course, students design, build, and fly radio-controlled electric propulsion aircraft. In a course on *Aerodynamics*, a case study from either industry or government is used to provide an authentic problem. Upper-level capstone courses are entirely problem-based. In these PBL experiences, students identify problems of interest to them and experiment to find solutions, as well as design complex systems that integrate engineering fundamentals in a multidisciplinary approach. This paper describes several problem-based learning experiences in undergraduate aerospace engineering at MIT within a four-level framework for categorizing problems. It presents the learning theories that underlie the success of PBL, identifies the basic characteristics of PBL, critical features in the design of problems, and effective methods for assessing PBL.

Introduction

Interest in problem-based learning (PBL) arose in higher education in response to criticisms that programs in professional areas, *e.g.*, medicine, engineering, failed to equip graduates with the problem-solving skills required for a lifetime of learning.[1-2] Problem-based learning has now become a widespread teaching method in disciplines where students must learn to apply knowledge not just acquire it.

Problem-based learning derives from the theory that learning is a process in which the learner actively constructs knowledge. Learning results from a learner's actions; instruction plays a role only to the extent that it enables and fosters constructive activities.[3] Three major theoretical principles support the practice of PBL:

1) Learning is a constructive process
2) Knowing about knowing (metacognition) affects learning
3) Social and cultural factors affect learning.

Learning as a Constructive Process

Learning occurs when students are able to make connections of new information with knowledge and experiences they have already assimilated. Explicit attention should be paid to students' existing knowledge base and the activation of this knowledge to provide a framework for learning. Facilitating the processing of new information and helping students to construct meaningful connections is regarded as the basic requirement for teaching and learning.[4] Problem-based learning promotes students' active engagement with learning. Learning becomes an act of discovery as students examine the problem, research its background, analyze possible solutions, develop a proposal, and produce a final result.[5] Not only is this active learning more interesting and engaging for students, it also develops a greater understanding of the material since students find the information for themselves and then actively use the information and their skills to complete the project.

Metacognition

Metacognition is the process of knowing how one knows or learns. Good students can detect when they understand – or do not understand – new information, and know when to use different strategies to decipher new knowledge and experiences. They are able to judge the difficulty of problems and assess their own progress in resolving them. Problem-based learning gives students opportunities to monitor their own learning and assess their own progress.

Social and Cultural Influences on Learning

Effective instruction is placed in the context of complex and meaningful problem-solving situations. The emphasis is on learning in the context in which students will work later on. Students study concepts over an extended period of time in a variety of contexts. Students make a greater attempt to understand and remember when they see connections between the materials they study and their own lives. Problem-based learning deals with problems that are as close to real life situations as possible.[6] In small group work, the learner's exposure to alternate points of view is a real challenge to initial understanding.

Goals and Characteristics of Problem-Based Learning

The main goal of problem-based learning is to provide students with opportunities to apply knowledge, not just acquire it. PBL focuses on problem formulation as well as problem solving. It seeks to simulate real-world engineering research and development. Barrows describes the main features of PBL in this way:

- Learning is student centered, *i.e.*, students make choices about how and what they want to learn.
- Learning occurs in small student groups and promotes collaborative learning.
- Teachers are facilitators or guides or coaches.
- Problems form the organizing focus and stimulus for learning.
- Problems are a vehicle for the development of authentic problem-solving skills.
- New information is acquired through self-directed learning.[7]

Barrows believes that acquisition of an integrated knowledge base and development of effective self-directed learning and teamwork skills must precede problem-based learning.

The success of problem-based learning is contingent upon the design of good problems. Gijselaers suggests these guidelines in designing problems:

1) Effective problem descriptions focus on student-generated issues and do not include lists of questions to be answered.
2) Problems are ill-defined, complex, multi-faceted in which there is no single best answer.
3) Effective problems should result in motivation for self-study.[8]

Delisle describes problem design for elementary and secondary education, but his suggested checklist has useful applications to higher education. The problem statement should be grounded in student experience, be curriculum based, allow for a variety of teaching and learning strategies and styles, be unconstrained, focus on a question, and be assessable.[9]

PBL in Aerospace Engineering at MIT

About five years ago, the Aeronautics and Astronautics Department at MIT launched a new strategic plan committing faculty and instructional staff to major curriculum reform. Program and learning outcomes were identified and validated with key constituent groups, new teaching and learning strategies were initiated, and laboratories and workshops were built or re-modeled to emphasize student-centered education. Major resources, both personnel time and funding, were committed, as well. Although problem-based learning is a key feature, it is not the organizing principle of the curriculum. The new aerospace curriculum is set in a real-world engineering context of a complete product life cycle, *i.e*., conceiving, designing, implementing, and operating (CDIO), with design-build experiences integrated throughout the program.

Design-build experiences are sequenced from more simple projects to highly complex systems. In an early freshman-year experience, *Introduction to Aerospace and Design*, students design, build, and fly radio-controlled lighter-than-air (LTA) vehicles. In the sophomore-year *Unified Engineering* course, students design, build, and fly radio-controlled electric propulsion aircraft. In an advanced course in *Aerodynamics*, a case study from either industry or government is used to provide an authentic problem. In the past, Lockheed Martin Tactical Aircraft Systems provided scenarios for design projects that are typical of those encountered in the aircraft industry. Upper-level capstone courses are entirely problem-based: *Experimental Projects Laboratory Space Systems Engineering*, and the *CDIO Capstone Course*. In these PBL experiences, students identify problems of interest to them and experiment to find solutions, as well as design complex systems that integrate engineering fundamentals in a multidisciplinary approach.

The Director of *The Learning Lab for Complex Systems* in MIT's Aero/Astro Department, has proposed a useful framework for categorizing problem-based learning approaches.

(See Table 1.) It suggests four levels of problems to address basic sciences, core and advanced engineering topics, and systems approaches.

Table 1. Integration of Problem-Based Learning Into Undergraduate Engineering Education

Levels	Mathematics and Sciences	Core Engineering	Advanced Engineering	Systems
1. Problem Sets	x	x		
2. Mini Labs		x	x	
3. Macro Labs			x	x
4. Capstone Labs			x	x

Level 1. Problem Sets
These are the traditional problems found in most engineering courses. They tend to be fairly structured, and often have known solutions (at least to the problem designer). All students solve the same problems, sometimes individually, sometimes in groups. Problems require a relatively short time to solve.

Level 2. Mini Labs
These are short lab sessions in a structured environment, *e.g.*, measuring or observing certain engineering phenomena or data. Problems, designed to be completed in one or two sessions, can be "mass-produced", *i.e.*, each student team solves the same problem as other teams. Examples at MIT include truss labs in *Unified Engineering*, pitot tube calibrations in the wind tunnel in *Aerodynamics*, tests of various aerodynamic decelerators in the *Introduction to Aerospace and Design*, a tracking/cueing laboratory simulating human responses in *Human Factors Engineering,* and the use of flight simulators in various undergraduate engineering courses.

In *Human Factors Engineering*, for example, students work with an automobile driving simulator over a period of three weeks. Working in groups of five or six, students solve problems requiring them to conceive and design solutions that can be tested on the automobile simulator. The teaching staff provide ideas and help students define the constraints of the simulator situation. (This simulator has now been replaced by the *Microsoft Flight Simulator 2000*.)

Level 3. Macro Labs
Problems at this level are longer in duration than previous levels, ranging from several weeks to a full term. Problems are significantly more complex, entailing more planning and staff support. Examples at MIT include projects in the *Experimental Projects Lab* course, wind tunnel testing, aircraft models, mechanical projects in *Aerodynamics*, lighter-than-air blimps in *Introduction to Aerospace Education*, and electric aircraft design in *Unified Engineering*.

In the *Experimental Projects Lab* course, for example, students work in pairs to master the methods, processes, and techniques that are involved in conceiving, designing, constructing, executing, and documenting an experimental project. Course instructors guide the process and provide content for experimental design. Faculty project advisors serve in roles similar to thesis advisers.

Level 4. Capstone CDIO Labs
This level consists of capstone laboratory experiences that integrate core engineering disciplines in a systems context. The aerospace engineering program at MIT approaches engineering in a context of Conceive-Design-Implement-Operate (CDIO). In the capstone experience, all four phases of engineering are practiced. A strong research focus and funding, high complexity levels, and multi-term experiences typify capstone labs. Examples at MIT include autonomous satellites a sparse optical array project, and electromagnetic flight formation vehicles. These *Level-4* projects engage students, instructors, and researchers for three semesters.

Experiences at Levels 3 and 4 meet the criteria for PBL as described earlier. They are student-generated, unconstrained, complex, multi-faceted, and highly motivating to students. While experiences at Levels 1 and 2 are more structured and straightforward, they provide valuable introductions to problem formulation and the use of tools for research and discovery. Students find these "designed-for-success" experiences highly satisfying, and these successes whet their appetites for more independent problem-solving situations.

Assessment of Problem-Based Learning

Assessment of PBL experiences is multimodal and ongoing. Methods include laboratory journals, technical briefings, design reviews, technical reports, collaborative teamwork assessment, design portfolios, peer assessment, and self-assessment.[10] Faculty serve primarily as advisors and coaches, providing extensive feedback to students throughout the learning experiences.

In *Introduction to Aerospace and Design*, where students design, build, and fly radio-controlled LTA vehicles, they are assessed with design reviews, portfolios, and the final LTA race competition.[11] In the *Unified Engineering* aircraft design project, second-year students analyze the fundamentals of aerodynamic performance, stability, and propulsion in problem sets as well as hands-on assembly and flight of radio-controlled electric propulsion aircraft. Similar to the first-year course, assessment techniques include problem sets and design reviews, as well as a competitive final event. In *Aerodynamics*, students design and perform aerodynamic analyses including both computational and experimental methods. In addition to these analyses, students are assessed with concept quizzes, oral exams, and self-assessment methods. In the *Experimental Projects Lab*, students are assessed with laboratory notebooks, design reviews, technical briefings, and written reports. In *Space Systems Engineering*, students design a complex space system. They are assessed with design reviews, technical briefings, written documents, teamwork, project organization, and integration of more than one discipline.

In addition to assessing cognitive skills development and achievement, affective outcomes are also evaluated. It is important to assess students' confidence in problem solving, their willingness to engage in solving challenging problems, and their sense of control of the problem-solving situation. These attitudes can be assessed with observation, interviews, portfolios, journals, and other forms of self-assessment. In some PBL experiences, students are graded individually for group projects when the work of each individual is clearly identifiable in the final project.

Feedback from instructors about the use of problem formulation and problem solving in the aerospace engineering program at MIT has been generally positive. At the end of each term, instructors are asked to write Reflective Memos in which they describe the course objectives, teaching and learning approaches, and student outcomes. They find that PBL is rewarding and stimulating for all participants. One instructor who has had success with Level 2 problems with teams of two students is eager to introduce Level 3 problems with larger teams. The main constraints are resources in terms of time, cost, and space. PBL is much more time consuming than anticipated both for faculty and students. Moreover, the invention of new projects each year is sometimes difficult.

Students are also very positive about the involvement of industry and the use of real-world examples in their work. In end-of-term course evaluations for 2000-2001, students were asked to rate the effectiveness of different teaching and learning strategies, using a 3-point scale of *not effective*, *somewhat effective*, and *very effective*. Table 2 shows that percentage of students in the courses with PBL experiences who found the teaching and learning experiences to be *very effective*. Among items that describe the course overall, two are related to PBL experiences. Students were asked to agree or disagree (using a standard Likert agreement scale) that the course was relevant and that overall it was worthwhile. The results are also found in Table 2. The overall ratings (worthwhile course) for courses with PBL experiences are among the highest among all undergraduate aerospace engineering courses in the department.

Table 2. Effectiveness of PBL Methods and Satisfaction with Course

Course	**Hands-On Experiences (% Very Effective)**	**Term Projects (% Very Effective)**		**Relevant (% Agree and Strongly Agree)**	**Worthwhile (% Agree and Strongly Agree)**
Intro. to Aerospace Design	85	88		58	63
Unified Engineering I	78	--		97	94
Unified Engineering II	48	--		95	94
Aerodynamics	68	64		90	82
Experimental Methods I	67	70		92	96
Experimental Methods II	78	65		78	74
CDIO Capstone (Part I)	75	50		100	75
Space Systems Design	72	94		100	83

Students were asked to comment on the best parts of the course. These few sample responses represent the overall positive response to problem-based approaches.

> The LTA [Lighter-Than-Air] Vehicle design process, from PDR [Preliminary Design Review] through Trial Day (and soon enough, through Race Day), is enjoyable and easy to understand. I wish I could have spent more time working on the blimp.
>
> I think the best parts of the course are the projects: the LTA and the articulated figure. I think hands-on time is the most important.
>
> Hands-on projects such as the delta design, articulated figure, and of course, the LTA project were the best
>
> Thoroughly enjoyed actually doing the research and working toward understanding the results. Also, enjoyed the oral presentations.
>
> The project involving a real case study was the best part by far.
>
> The design project is a lot of fun and seems like a real world application of the material.
>
> The concept of following one project all the way through from planning to testing is great. The faculty-student ratio is good, and the faculty are very engaged and enthusiastic about the project.

Summary

Problem-based learning and design-build experiences are integrated across the undergraduate aerospace programs at MIT. Using a four-level framework to classify PBL experiences ensures a reasonable progression from highly structured to largely unconstrained and complex problem situations. Early experiences are designed to be success experiences with greater levels of faculty direction and support. As students' confidence and initiative grow, they are introduced to more complex, unknown, real-world applications.

In these PBL experiences, MIT students find that learning is more interesting and engaging, and that they develop a greater understanding of engineering science and core engineering fundamentals because they find the information for themselves and actively use the information to complete their projects. Through self-assessment and colleague assessment activities, students are able to monitor their own learning, assess their progress, and evaluate their own and their colleagues' contributions to the success of the projects. Moreover, with an emphasis on learning in real-world contexts, students see the connections between the subject matter and their own professional interests.

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