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How to develop engineering students' problem solving skills using cooperative problem based learning (CPBL)

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ABSTRACT

Problem solving has been identified as the top priority attribute in engineering graduates for the 21st century. Nevertheless, the question remains on how to actually develop skills for solving real world problem in engineering students. Cooperative problem based learning (CPBL) has been shown to significantly enhance problem-solving skills among engineering students in a typical course. CPBL is the integration of cooperative learning (CL) in the problem based learning (PBL) cycle to enable efficient and effective implementation in a class of up to sixty students with one instructor acting as a floating facilitator. Research on students' perception of CPBL also showed that while many students may not initially like the drastic change from the usual "spoon-feeding" culture to learning inductively through CPBL, most of them were gradually won over as they go through several problems and CPBL cycles, especially when they realized the enhancement in skills and knowledge that they gained through the technique. This paper puts forth a summary of the research findings on CPBL, and explains how to conduct CPBL in developing and enhancing problem solving skills in engineering students.

Keywords: problem-based learning, cooperative learning, problem solving skills

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1. INTRODUCTION

The 21st century calls for engineering graduates who can solve novel, complex, multidisciplinary problems in a fast-changing, borderless world. Various reports on the current and future engineering education from throughout the world highlighted the importance of problem solving skills among engineering graduates. For example, the UK Royal Academy of Engineering reported from a study conducted amongst industries that the top most quality among engineering graduates that employers desire is the ability to transfer and use their knowledge and skills into the work place setting, to solve real world problems.[1] In another instance, in accordance with the needs of the stakeholders and direct compliance of the Washington Accord requirements, six of the twelve program outcomes put forth by the Malaysian Engineering Accreditation Council explicitly contains the phrase complex engineering problems.[2]

Currently, most engineering programs focus more on content rather than skills. Curricula based on specific knowledge are built from the bottom up, with content identified first, rather that the outcomes of what students should be able to do upon graduation, resulting in graduates who cannot comprehend and address big problems.[3,4] The future engineering curricula should be built around developing skills and not around teaching available knowledge. Engineering educators must teach methods and not solutions. Even if problem solving is taught to engineering students, it is taught in a way that is contrary to real life practice in engineering. Almost all the time engineering students are taught to solve well-structured problems with a single solution, which are inconsistent with the nature of the problems they will need to solve in their real life practice as engineers.[5] Well-structured, closed problems that are amenable to a single correct solution are at one end of spectrum, and ill-structured, open-ended problems that are not amenable to such a solution, are at the other end.[6] Therefore, there is a discrepancy between what learners need (complex, ill-structured, open-ended problem solving experience) and what engineering education provides.[6,7]

The most important question now is: how to develop the ability to solve real world problems among engineering students? According to constructive alignment (CA), to attain a desired outcome, students must go through teaching and learning activities as well as assessment tasks that should support the attainment of the outcome.[8,9] Thus, students should solve engineering problems and be properly assessed in their courses. It is not surprising, therefore, when Stroble[10] urged engineering educators to better understand the nature of work place problem solving especially for instructional and educational strategies that heavily utilize problems like problem based learning (PBL). Savery[11] related constructivism (which is the philosophical view of how people came to understand), to the practice of instruction. He examined PBL, which he considered the best exemplars of constructivist learning environment.

While PBL is recommended for developing problem solving skills, attaining the required depth of knowledge and skills in students using this student-centered technique is not an easy task, because problem solving is a complex skill that requires supporting skills, such as critical and creative thinking, self-directed learning, team working, communication, and many others, that must be developed too. In fact, efforts to get students to go through them may fall flat without providing the necessary support for developing the supporting skills needed, leading to assertions that PBL does not work or are not suitable in certain cultures.

This paper puts forth steps in implementing cooperative problem based learning (CPBL), which is the infusion of cooperative learning principles into the problem-based learning cycle. CPBL has been shown to be effective in supporting students to develop team-based problem solving skills step-by-step among engineering students. Designed based on Bransford's "How People Learn" (HPL) framework[12] and Biggs' constructive alignment (CA), the CPBL framework guides students and facilitators to go through the process in a systematic and step by step manner, providing support in terms of giving the big picture and the break-down into simpler parts, making the complex practice of problem solving more manageable. A summary of research that have been conducted on CPBL is discussed, especially in relation to ensuring effective implementation among students in a typical engineering course.

2. THE COOPERATIVE PROBLEM BASED LEARNING MODEL

PBL is a philosophy that needs to be adapted to the specific condition and environment of the institution and the nature of the field in which it is applied. This can be seen in the different models of PBL implementation throughout the world, ranging from the small group medical school model, the project organized model to the one-day-one-problem model.[13–16] Most PBL models, however, can be expensive because they require intensive manpower, infrastructure and institutional support. Small group implementations typically consist of a maximum of ten students, while small classroom consists of about twenty students. This is because a dedicated facilitator is required to provide cognitive coaching and support for learning. Without the required support and facilitation, students will not be able to develop and reach deep learning, and would thus fail to solve the problem. Unfortunately, this renders most PBL models to be unsuitable for a typical engineering course, which would normally consist of thirty to one hundred students, or even more.

To make it possible to implement PBL in a medium sized course of not more than sixty students (divided into learning teams of three to five students) with one instructor, Cooperative Learning (CL) principles are integrated into the PBL cycle based on constructive alignment (CA), thus becoming cooperative problem based learning (CPBL). In a proper cooperative learning (CL) environment, part of the monitoring, support and feedback can be attained from peers, especially team members, instead of solely relying on the facilitator. In fact, support can be further enhanced by developing the whole class into a learning community. To ensure good team working, the five principles of cooperative learning[17] must be emphasized and promoted throughout the CPBL cycle. The five CL principles are: positive interdependence, individual accountability, face to face interaction, appropriate interpersonal skills, and regular group function assessment.

The CPBL process consists of the same three phases of the PBL process, as shown in Figure 1. However, each phase is expanded to incorporate CL principles to ensure a functioning cooperative team. Phase 1 consists of the problem identification and analysis stage. Phase 2 is the learning, application and solution formulation stage. Phase 3 is the generalization, internalization and closure stage. In each phase, the individual activities are designed to enhance learning and accountability, which will be strengthened with team-based activities, and further supported in the overall class activities to form a learning community. The framework in Figure 1 can be used to visualize the CPBL process to support students in grasping the overall requirements of the whole process, as well as the significance of each step in terms of the outcomes and activities in each block as they go through each of the three phases in the CPBL cycle.

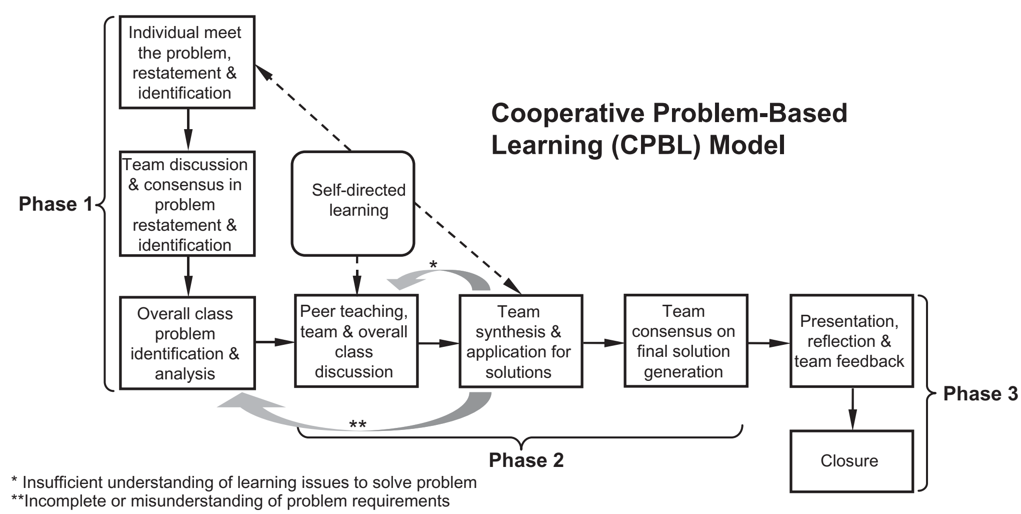

Figure 1. Cooperative problem based learning (CPBL) model.

In addition to the constructivist underpinnings of PBL and the social interdependence underpinnings of CL, CPBL is inspired by Bransford's "How People Learn" (HPL) framework,[4] while the step by step process is designed using Bigg's Constructive Alignment (CA).[8,9] The HPL framework can be utilized for designing learning environments through four overlapping lenses, which are knowledge centred, learner centred, assessment centred and community centred.[4] CA requires the outcomes to be aligned with assessment tasks and teaching and learning activities, which should be based on the constructivist approach, where students go through a learning environment that gives them the opportunity to construct knowledge or skills specified in the outcomes.[8,9] A detailed description on the development of the CPBL framework and principles used can be seen in Mohd-Yusof et al.[18–20]

3. SCHOLARLY EFFORTS AND RESEARCH IN CPBL

Small scale studies had started early on during the initial implementation phase of PBL to determine student acceptance and extent of understanding of the content learned.[21] The model used have since been refined and studied further by several PhD in Engineering Education candidates in Universiti Teknologi Malaysia.

Helmi[22] studied the impact of CPBL on engineering students after undergoing a course that used CPBL for the whole of the semester. The quantitative analysis provided evidences that students significantly enhanced their team-based problem solving skills.[18,19,23] The qualitative analysis showed how problem solving skills among engineering students was achieved through CPBL. Factors that contributed to the enhancement are categorized under four spotlights, which demonstrated how students improved their problem solving elements, motivation and learning strategies, and team working, which contributed a lot to students' problem solving assets, thus enhancing their engineering problem solving skills. These findings proved that CPBL can be effectively implemented, and is a very powerful and effective method of learning for typical engineering courses.

In a study by Phang et al.,[24] students' perception and the impact on learning throughout the semester as they go through CPBL by a lecturer who is conducting CPBL for the first time were analyzed. This research was initiated because even though CPBL can be very a very powerful technique, implementing and facilitating CPBL can be rather complicated, especially if the course where it is implemented is the only one using the technique among others that use a more traditional lecture-based method. Students who face CPBL for the first time will typically feel shocked over such a drastic change in the teaching and learning method and will normally go through the typical trauma cycle before reaching a higher level of performance.[14] A phenomenological research design was carried out through non-participant observations, unstructured interviews and students' written self-reflections which were collected at the end of every problem. Analyzing the qualitative data obtained from students in the class, four types of changes on student perceptions can be seen as students undergo the CPBL learning process:

(a) Those that held positive perception about CPBL from the beginning until the end
(b) Those that held negative perception from the beginning until the end
(c) Those that changed from positive in the beginning to negative perception at the end
(d) Those that changed from negative in the beginning to positive perception at the end

While the majority of students held positive perception towards CPBL in the end and managed to gain a variety of skills, it is interesting to note that factors that caused students who have a positive perception to appreciate CPBL are also those that caused the negative perception. The two main factors are time management and effort required to learn in a constructivist environment. Insights from the analysis of the findings shows the gaps that need to be addressed in supporting, design scaffolding and facilitating students through the myriad of emotions that they go through to finally allow them to develop positive perception so that they may gain from CPBL.

3.1. Implementing CPBL to develop problem solving skills

The effort to implement CPBL in a typical course in a semester can be divided into two stages. The first is the planning and preparation stage, and the second is the execution of the CPBL phases. The planning and preparation stage consists of the following steps:

a. Identify outcomes of course to be taught using CPBL, and the corresponding content
b. Craft problem for attaining the outcomes identified
c. Plan the class activities according the CPBL phases
d. Determine the support activities required to attain the outcomes, if needed

The execution stage consists of the following parts:

a. Conduct Phase 1 of CPBL
b. Provide support and/or resources if necessary
c. Conduct Phase 2 of CPBL
d. Conduct Phase 3 of CPBL

3.2. Planning and preparation stage

The planning and preparation stage is very important in determining the success of CPBL implementation. CPBL cannot be implemented in an ad-hoc fashion without going through this stage. If CPBL is to be implemented for a whole semester, then this stage has to be completed before the start of the semester. For a smaller scale implementation, such as a problem spanning over four weeks, all the planning and preparation should be completed before the start of execution of CPBL.

The first step in this stage is to identify the course outcomes that will be covered through CPBL. Once the outcomes have been determined, the corresponding course content and taxonomy level is identified. This content are the learning issues of the problem to be crafted.

The next step is to craft an unstructured problem that serves to contextualize the knowledge and engage learners in learning. The problem is designed so that the learning outcomes can be achieved when students have gone through the process of solving the problem. In accordance with CA, the outcomes of the problem consists of the content, skills and attitude outcomes at the desired level. Contextualization means that the smaller learning issues and tasks are anchored to a larger task or problem, that illustrates the relevance of the objective and provides meaning of the tasks to the learners. In addition, connection with prior knowledge also needs to be established, requiring instructors who craft the problem to determine the level of prior knowledge that students have acquired. This meets the requirement of the knowledge centred aspect of the HPL framework. Adding the prior knowledge connection to the problem provide an opportunity to find out preconceptions in students, thus addressing the learner centred aspect of the HPL framework. The open-ended problem must be realistic (if not real) and draws the learners in with meaningful roles and possible outcomes that is beneficial. The complexity and intricacy should draw students in learning, deliberate on possible approaches to the problem and come up with possible solutions, and finding the best solution for the problem, given the specific scenario. Students, in effect, should have ownership of the problem. A step by step guide to craft problems for engineering courses can be seen in Mohammad-Zamry et al.[25]

The duration given to students to solve the problem through the CPBL cycle must be decided. A small problem may take a week, while a complex one may take up to a semester. However, it is recommended that large problems are broken up into parts that are distributed throughout the semester, which can be completed in one or two cycles. This is crucial for students learning with CPBL for the first time, because they do not have the ability to solve large complex problems, and would most likely delay putting in effort until just before the due date, resulting in a poorly thought out solution. Proper planning must be made to give time for students to go through the three phases of CPBL step by step to guide them in solving the problem. The learning issues that students need to learn before they can solve the problem should be manageable within the duration given. For students who are new to CPBL, it is recommended that the whole CPBL cycle should be between one to three weeks.

Finally, it is necessary to establish if students need additional support to develop skills required to undergo CPBL. For example, if students are not comfortable thinking and sharing their ideas with each other, simple activities can be used to initiate specific thinking skills and verbalizing as well as constructing thoughts. Formal CL techniques, which are more intricate, may require the integration with informal CL activities as scaffolding for students. These simpler to implement techniques, in turn, can be integrated as scaffolding for supporting students who face challenging tasks in CPBL for the first time. In addition to providing support for skills and cognitive development, emotional and motivational support is also necessary. Students who had to endure a drastic change in the learning environment, such as CPBL, would normally undergo the typical emotions that psychologists identify similar to those who face trauma.[14] Therefore, it is essential to provide emotional support to motivate the students.

3.3. Execution stage

The execution stage is the actual implementation of CPBL during the semester. It is crucial for all facilitators involved to understand the intended outcomes of the problem. Instructors should be well trained in facilitation skills and be well versed on the underpinning principles of CPBL to enable them to ascertain the appropriate guidance and scaffolding to support students. In addition, the knowledge of the philosophies act as a compass in facilitating students through the CPBL process. In addition to the phases, execution of scaffolding for supporting students is important. Scaffolding activities are not necessarily separated from the CPBL phases. The activities can in actually be integrated into the CPBL cycle. Some of the activities may provide support for students to do some of the steps in CPBL. In fact, the CPBL framework itself is a scaffolding for students in solving the problem.

Phase 1 aims to train students to think first when facing a problem, preventing them from jumping straight to find the solution without really understanding its requirements. The outcome is for learners to explain and analyze the problem, defining in terms of existing knowledge, and new knowledge needed, causing them to recall prior knowledge, thus making connections with new ones. Students were asked to individually restate and identify the problem in their own words, as illustrated in Figure 1 and explained in Table 1, which they submit at the beginning of class. Individual submission drive students towards individual accountability because it pushes each of them to think about the problem and prepare before coming to class. Consequently, the team discussion to reach consensus on the restatement and identification of the problem can be efficiently carried out in class, followed by an overall class discussion, which allow instructors to assess students' ability to understand and define the problem, as required in constructive alignment. Instructors should facilitate in a way that probe students into the higher order thinking region, rather than providing straight forward yes or no answers.

Table 1. Phase 1 TLA mapped to educational principles.

TLA	Description of TLA	AT	Outcomes
Individual PR&PI	Post or give problem a day or two prior to class. Before class, students read and prepare individual PR&PI for submission.	Individual PR&PI	Restate in own words and identify problem
Team discussion & consensus	In class, teams discuss to find consensus for team PR&PI and draw up action plan and assign learning issues to each member to prepare for peer teaching, within a given time in the class. May request presentation of team PR&PI.	Team and overall class feedback on PR&PI discussed	Explain & discuss PR&PI to come up with the best for the team, team communication
Overall Class PR&PI	In-class discussion of PR&PI, where students may be randomly called to provide team answer and discuss differences. Conduct discussion to promote learning community among all students.	Feedback on overall PR&PI discussed	Analyze various teams' PR&PI and finalize learning issues for the problem

Phase 2 aims to train students to fill in the gap in their knowledge that they have identified in Phase 1 before solving the problem. The outcome is for learners to be able to do self-directed learning to fill their knowledge gaps, synthesize and apply them to formulate the solution. During this phase, students learn together, evaluate different approaches to solve the problem and justify the choices made., as shown in Table 2. Students individually prepare peer-teaching notes and submit a copy. Other than promoting accountability, they learn to construct new knowledge by extracting important concepts and information, explaining what they understand, and inquiring about what they do not fully understand to develop abilities to learn through questioning. Next, they learn in their team, followed by an overall class discussion. Team peer teaching drives them to deep learning, especially on technically challenging material, where they would easily give up if they had to study alone. Learning in a team that they are comfortable with encourages students to share what they learned, and feel safe to ask questions, which leads them to be more confident in sharing their understanding and asking questions in the overall class discussion. Facilitators monitor the overall class discussion to assess students' understanding of the learning issues, and probe them so that they may reach the required depth of understanding. Then, all collated information and knowledge is shared and critically reviewed, before the relevant ones can be synthesized and applied to solve the problem. This step can be iterative, where students may need to re-evaluate the analysis of the problem, pursue further learning, reporting and peer teaching. This part is mostly performed outside the classroom, relying further on interpersonal skills especially in coming up with a consensus for the best answer.

Phase 3 aims to invoke critical evaluation of solutions, develop students' meta-cognitive abilities in reflecting and tie-up loose ends. The outcome is to have learners critically determine the best solution

Table 2. Phase 2 TLA mapped to educational principles.

TLA	Description of TLA	AT	Outcomes
Peer T&L	Students individually prepare peer T&L notes, and conduct team peer T&L outside of class before overall class peer teaching session. Individual peer T&L notes submitted and an overall class peer T&L discussion coordinated by a team assigned in the previous class. May give tutorials, quiz or mini lecture if required.	Individual peer T&L notes. Feedback on class discussion. Quiz or tutorial on important concepts	Construct information to learn new content individually and in a learning community to attain deep learning
Synthesis & application	Students synthesize knowledge and information together as a team and use them to come up with possible solutions. Conduct progress check for problems with a duration of more than 2 weeks.	Progress check/report, e-learning forum	Connect & integrate learning issues together and with existing knowledge for deep learning. Apply different approaches to solve problem
Consensus on final solution	Students reach a consensus on a solution that is deemed to be the best to all team members, with proper justification.	Final solution or product	Analyze possible approaches to get best solution

for the problem and use meta-cognitive skills to internalize and generalize concepts and skills learned. Students submit solutions, in the form of deliverables that is aligned to the outcomes, as shown in Table 3. The facilitator probes students during discussions to determine acceptable solutions, and justify their choice of the best solution. Allowing a thorough discussion of the solution and concepts is important to gauge students' level of learning, whether deep understanding was reached. During closure, feedback is given on the possible solutions, as well as identify the best solution, serving as part of the formative assessment. Generalization should include connections between concepts and applications in other areas. This is necessary to facilitate knowledge transfer to other types of applications. To strengthen the community centred aspect in developing team working skills, a team-based post-mortem on the process and performance must be conducted in class. CPBL stresses the importance of developing meta-cognitive skills through reflection so that students may analyze their own performance, thus continuously learning and improving themselves. This step must be taken seriously; otherwise, students will lose the opportunity to discover the learning experience that they went through while solving the problem.

Table 3. Phase 3 TLA mapped to educational principles.

TLA	Description of TLA	AT	Outcomes
Presentation, reflection, team peer rating and feedback	Final solution presented in class, with different solutions and approaches discussed. Conduct individual reflection, rate team members and provide written feedback on good actions to keep up and things to improve on. In-class discussion on overall team performance	Presentation or report. Reflection, peer and self rating, written peer feedback	Communicate and justify solution in oral or written form. Self & team feedback to evaluate learning process in developing meta-cognitive skills
Closure	Summarizes and generalizes important concepts in problem. Compare different approaches & solutions to suggest the best solution for the problem. May also include "what if" or variations in conditions in which the concepts may apply.	Feedback on solutions and final reports	Analyze variations in solution and conclude best approach for problem. Generalize learning issues learned to other situations.

4. CONCLUSION

This paper presents a summary of research on CPBL and steps on implementation to develop problem solving skills in students. Going through the three phases of CPBL and the scaffolding activities allow students to acquire supporting sub-skills for developing complex problem solving, which is essentially the requirement of engineering graduates for the 21st Century.

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