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# Application of Problem-Based Learning to Promote Critical Thinking Disposition Among Engineering Undergraduates*

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Previous studies have shown that the problem-based learning (PBL) is an effective approach for engineering education. This research explores the impact of the PBL approach on engineering students' critical thinking (CT) disposition. A quasi-experimental design with quantitative and qualitative data analysis was used. An experimental class with 61 students was taught with the PBL approach, whereas a control class of 63 students adopted the traditional lecture-based learning. A Chinese version of the California Critical Thinking Dispositions Inventory was used to evaluate the participants' CT disposition. Evidence collected from quantitative surveys and qualitative data indicates that: after a semester of teaching circuit theory with PBL, the CT disposition survey scores of students from the experimental class had significantly increased, while there were no significant differences between pre-tests and post-tests for the control class.

**Keywords:** circuit theory; critical thinking disposition; problem-based learning; engineering education

## 1. Introduction

Innovation in science and technology is the driving force for social and economic development, and what is crucial to students' innovation training is critical thinking (CT) ability among other things. With the social, economic, educational, environmental and health challenges, the 21st century no longer needs the teaching of soon-to-be obsolete facts, but the fostering of the CT ability at all levels of education [1]. To develop university students' CT ability is to cultivate their innovative spirits and skills for the survival in the information era and to eliminate superstition and blind faith for the advancement in the digital era. In fact, the students' critical thinking might affect their creative design ability remarkably [2]. Generally, teaching higher order cognitive abilities such as the CT ability has always been the ultimate goal of education in the world [3].

CT is a prerequisite in problem solving because it is a "purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which judgment is based" [4]. In this context, CT can be considered from two perspectives, namely skills and dispositions. Researchers from different fields agree that a critical thinker must possess both a set of thinking skills and the habits of mind necessary to use those skills. The latter could be called "critical spirit," or CT disposition. The ideal critical thinker can be characterized not merely by her/his thinking skills but also by how s/he approaches life and living in general [5]. CT disposition can be evaluated through surveys such as the California Critical Thinking Dispositions Inventory (CCTDI). CCTDI assesses how students feel when they approach the seven qualities: truth-seeking, open-mindedness, analytical tendencies, systematic tendencies, CT self-confidence, inquisitiveness, and cognitive maturity [6].

It is found that several ways may be used to develop CT ability: (1) offering specialized courses about CT; (2) embedding CT development into regular classroom teaching; and (3) developing hidden courses for CT. To effectively combine discipline teaching and CT training is more helpful. Studies have proved that teaching and learning modes such as collaborative learning [7–9], research-based learning [10, 11], Internet-based learning [12], project/case-based learning [13–16], inquiry-based learning [17, 18], and problem-based learning (PBL) [19–24] can promote students' CT ability. CT in an engineering context is well reported in the literature of teaching and learning but they just focus on the theoretical and conceptual frameworks. How CT ability is better promoted in engineering curricula remains unknown [25].

Amongst the teaching and learning modes, PBL is widely regarded as a successful and innovative approach for engineering education [26]. PBL is implemented by presenting students with a situation that leads to a problem for them to solve. Rather than finding a single correct answer, students interpret the question, gather additional information, create possible solutions, evaluate options, and present conclusions [27]. The key of

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PBL is to encourage students to "doubt" and "ask". In practice, the most important characteristic of the PBL method is that it creates a good learning atmosphere resulting in a positive attitude towards what are learned in general [28]. Evidence suggests that PBL enhances students' transfer of concepts to new problems, integration of concepts, intrinsic interest in learning, self-directed learning and learning skills [29].

Although PBL has been proved to effectively enhance students' CT disposition in course teaching, the implementation processes of the PBL approach varies widely. Literature did not come to the similar conclusion [20, 25, 30–32]. Potential factors, i.e., sample size, sample type, instruction type, gender, maturity, instrument, nationality, discipline, treatment duration, and group size may impact on the effectiveness of the cultivation of CT skills and disposition in light of PBL [20].

In this research, we take the course entitled Circuit Theory in Shanghai Jiao Tong University (SJTU) as a case and try to investigate how the PBL approach impacts on students' CT disposition. The research questions are: Can PBL promote the development of engineering students' CT disposition in teaching the course of Circuit Theory? What should be paid attention to when implementing PBL approach for Circuit Theory teaching? The research hypothesis is: PBL approach for Circuit Theory teaching can promote the development of students' CT disposition significantly.

## 2. Research Process

### *2.1 Research Description*

A quasi-experimental research with pre- and post-tests of experimental and control classes was implemented. The course of Circuit Theory is for sophomores, offered in the first semester to students in School of Electronic Information and Electrical Engineering, SJTU. The course is mandatory with 4 credits, and 12 classes were offered to cover over 800 participants annually. Students were from engineering majors, i.e., Electrical Engineering, Information Engineering, Electronic Science and Technology, Computer Science and Technology, Network Security Engineering, Automation, Microelectronics, Measurement and Control Technology and Instrument. Every student takes part in one Circuit Theory class freely according to his/her major, time available for class, recognition of instructors, etc.

Two classes were selected as the research subjects. Although these classes were taught by different instructors, the teaching materials, teaching contents and teaching progress were the same. One class adopted the PBL approach, while the other adopted the traditional lecture-based teaching methods. The instructors of the two classes were experienced professors and they had taught the course for over 20 rounds. They all understood the course contents very well.

The independent variable of the research is teaching methods, i.e. PBL method and traditional lecture-based method. The dependent variable is students' CT disposition.

### *2.2 Instrument Tools*

A Chinese version of CCTDI (CTDI-CV) was used to evaluate the participants' CT disposition. It was localized from CCTDI by Peng [33] and was widely used to measure Chinese students' CT disposition [34, 35]. CTDI-CV retains seven sub-scales as CCTDI with 10 items per sub-scale, including 30 positive items and 40 negative items. All responses to the items were rated on a six-point Likert scale ranging from one point for "strongly disagree" to six points for "strongly agree." The content validity index (CVI) of CTDI-CV is 0.79, with the sub-scale CVIs ranging from 0.6 to 1. The overall Cronbach alpha is 0.90 with sub-scale alphas ranging between 0.54 and 0.77. The reliability and validity of CTDI-CV is higher than the translational version of CCTDI. Thus, CTDI-CV can more suitably reflect the CT disposition of Chinese students.

### *2.3 Teaching Design of the Experimental Class*

The summary of PBL activities for the experimental class is shown in the Fig. 1. The PBL approach followed the basic procedure of PBL according to Maastricht model [36]. As shown in Fig. 1, we had arranged five tasks in the implementation of PBL approach:

(1) PBL group forming. At the beginning of the semester, the instructor solicited unanimous consent of the experimental class for applying PBL approach to the course. 61 students in this class freely chose their PBL group partners. Ten PBL groups had been set and every group had six or seven members with one chair and one scribe recommended by the group members. Group formation was finished in the end of the third week of the semester.

(2) Chair and scribe training. Good organization of the PBL activity is the guarantee of achieving reasonable learning results. The chair directs the interaction between group members to enable an effective discussion with respect to both process and content and the scribe supports the chair. Before the PBL approach starts, the instructor trained all the chairs and scribes for skills of correctly applying the PBL approach, such as organizing, structuring, summarizing and noting the discussion. This work was done by the instructors before the end of the fourth week.

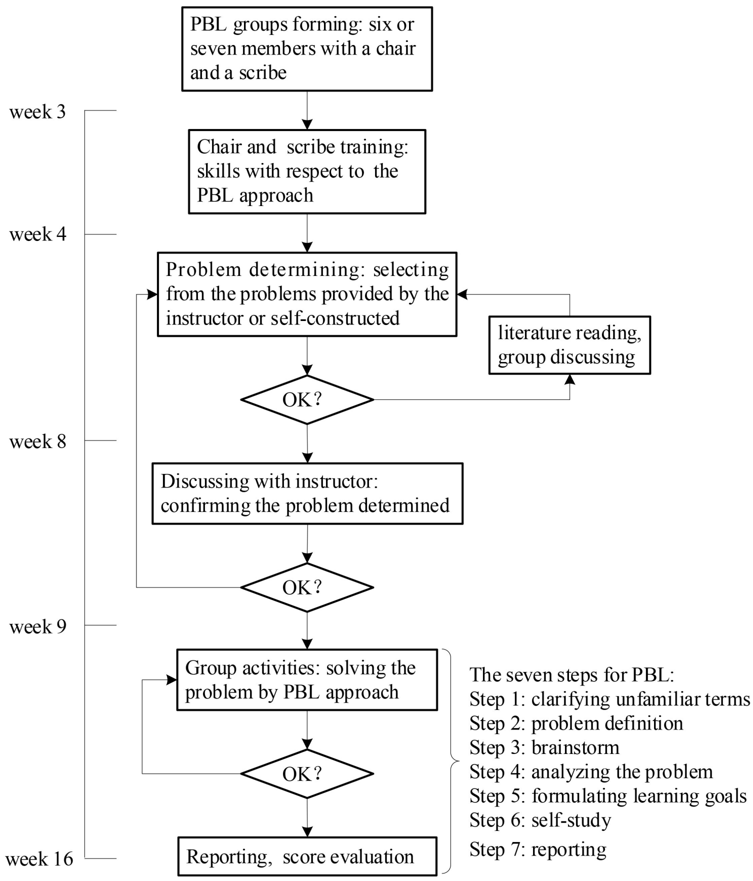


**Fig. 1.** PBL activities for the experimental class.

(3) Problem determining. The problems to be discussed were selected out from the problems provided by the instructor or self-constructed by the students before the eighth week. All the problems are new to the students. Group members could have one or two times of meeting to discuss and choose a problem of interest. If the problems from the instructor are out of the group's interest, the group can determine a new problem through literature reading. Ten problems selected by the groups are shown in Table 1. All the problems are related closely with the circuit theory, i.e., the content of the course.

(4) Discussing with instructor. The problems selected by students may be inappropriate for PBL approach, i.e., they may be too easy, or too difficult, or good structured, or close-ended. Each group should report the contents and tasks of the problem to the instructor. The instructor consults with the members to decide on the contents and tasks of the problem together. An appropriate problem for PBL approach could be determined through this step. For example, Group one proposed the problem "How to design an electric mosquito swatter circuit?" To solve this problem involves circuit devices and circuit design methods which are beyond the course content, so the instructor suggested to modify the problem as "How does electric mosquito swatter work?" which is relatively more suitable for solving. The work of discussing with instructor was done before the end of the ninth week.

(5) Group activities. Group activities aim to solve the problems. Seven steps involved in the PBL activities are shown in Fig. 1 according to the Maastricht PBL model. The steps can be summarized into three major stages: the preliminary discussion stage during which PBL groups are committed to get "what to know", "what not to know" and further "what need to know", the self-study stage during which group members search for relevant literature that can answer the questions in the learning goals, and the reporting stage during which students prepares for a project presentation and assessment.

Two rounds of group activities were organized during weeks 10–16. The first round was held during a 45 minutes lecture in the tenth week. The instructor would observe the discussion process of the groups and guide and promote the effectiveness of the discussion. All groups were required to finish the first five steps of the PBL approach, i.e., the learning goals should be formulated. During the

**Table 1.** Brief Summary of Group Discussion

| Group | Initial Title | Final Title | Problems | Group size |
|---|---|---|---|---|
| 1 | Design of electric mosquito swatter | Analysis and simulation of electric mosquito swatter | How does electric mosquito swatter work? | 6 |
| 2 | Design of negative resistor with operational amplifier | Same as initial title | What is negative resistor and how to design it? | 6 |
| 3 | Research on nonlinear first order RC circuit | Analysis of nonlinear first order RC circuit | How to analyze a nonlinear first order RC circuit? | 6 |
| 4 | Realization and application of negative resistor | Same as initial title | How to realize a negative resistor and how to apply it? | 6 |
| 5 | Realization of two-port circuit | Realization of two-port circuit based on operational amplifier and its application | How to realize a two-port circuit and how to apply it? | 6 |
| 6 | Discussion on capacitor and inductor using duality | Same as initial title | How to comprehend capacitor and inductor using duality? | 6 |
| 7 | Analysis of ADC and DAC circuits | Same as initial title | How do ADC and DAC work? | 6 |
| 8 | Analysis and application of gyrator | Same as initial title | How does gyrator work and how to apply it? | 7 |
| 9 | Exploring the mystery of two-port circuit | Same as initial title | What are the properties of the two-port circuit and how to apply it? | 6 |
| 10 | Design of programmable amplifier circuit with arbitrary step attenuation | Same as initial title | How to design a programmable amplifier circuit? | 6 |

**Table 2.** Summary of CTDI-CV Survey

| | Class size | Valid QNRs/ total QNRs (pre-test) | Valid QNRs/ total QNRs (post-test) | Valid paired QNRs | Pre-test date | Post-test date |
|---|---|---|---|---|---|---|
| Exp. class | 61 | 59/61 | 56/61 | 56 | 2021/09/13 | 2022/01/05 |
| Con. class | 63 | 54/63 | 53/63 | 51 | 2021/09/13 | 2022/01/05 |

discussions, the chairs and scribes would be responsible for organizing and recording. In the next two weeks, all the members would finish self-study outside the class. They could hold meetings for discussion. The instructor joined the QQ or WeChat[1] of each group and answered students' questions arising from self-studying on the line. The second round, which was somewhat similar to the first round was finished in the thirteenth to fifteenth week. In this round the discussion focused on self-studying outcomes to form more accurate problem solutions and preparing for report writing and presentation. Outcomes of PBL approach were demonstrated and evaluated in the sixteenth week.

Regardless of being in-class or after-class activities, the instructor encouraged students to think carefully and listen to others' views before raising questions. The instructor also encouraged students to exchange views mutually. From the beginning to the end, the instructor was positioned as the observer, discoverer, guider and promoter, not just as the knowledge imparter.

[1] QQ and Wechat are social media platforms widely used in China. They have more functions than Facebook, Twitter and Instagram.

## 3. Results

### *3.1 CT Disposition*

The CTDI-CV questionnaire was used to investigate possible changes in the experimental and the control classes. Table 2 shows the basic information of the questionnaire data. When the student ID number is the same in the pre-test and post-test, the two questionnaires will be effectively paired.

The results of the participant's CT disposition are shown in Tables 3 and 4. The paired sample *t*-test results indicate that the pre-test mean score (317.82) is significantly higher than that of the post-test (303.47) for the experimental class. By contrast, the paired sample *t*-test results indicate that no significant CT disposition difference was found in the control class. These results indicate that applying PBL approach in Circuit Theory teaching has significantly improved the students' CT disposition.

**Table 3.** Mean Scores and SD of Paired Samples of the Experimental and Control classes

| | Experimental class | | Control class | |
|---|---|---|---|---|
| | Pre-test | Post-test | Pre-test | Post-test |
| Mean | 303.47 | 317.82 | 302.41 | 303.42 |
| SD | 25.01 | 25.23 | 31.87 | 36.78 |

**Table 4.** Paired Sample *t*-Test for CT Disposition ($\alpha$ = 0.01)

| | | | | 99% confidence interval | |
|---|---|---|---|---|---|
| | *t* | df | *p* | Lower | Upper |
| Exp. class | 5.812 | 55 | 0.000 | 7.95 | 21.45 |
| Con. class | 0.115 | 50 | 0.911 | –20.44 | 22.32 |

We further computed the scores of the seven aspects of CT disposition of the experimental class. As shown in Table 5, for the experimental class, the CT disposition qualities of truth-seeking, open-mindedness and cognitive maturity had no significant difference between the pre-test and post-test, while there were significant differences in the other four qualities.

### 3.2 *Teaching Observation*

We observed teaching activities from different angles to probe if the teaching and learning is successful or not. Feedback on the courses was collected by asking the students to complete a questionnaire on the Internet anonymously. At the end of the semester, a survey was conducted in the experimental and control classes. The questionnaire includes six scale questions and one fill-in-the-blank question as shown in Table 6. Question 1 to 4 were common to the experimental and control classes while question 5 to 7 were only for the experimental class.

The responses to these queries, shown in Table 6, indicate that the PBL students are slightly more satisfied. Students in experimental class gave a higher grade to the course than that of the control class. The PBL students do not think they have made an undue effort for the course while the control students even think a little bit less work have been put in for the course. Students in both classes feel well in learning the course matter but the PBL students feel a bit better than the control students. The mean score of the experimental class for question 5 is 4.27, indicating that the PBL students are motivated. Consequently, the PBL students had a learning experience with more fun (mean score 4.01) than the control students (mean score 3.81). The results of question 6 are a measure of the degree of motivation. The mean score here is 3.61. This result can be interpreted to mean that the students feel that the PBL method drives them to be more active and involved in the course.

Forty three students have answered question 7. The open feedback shows that the vast majority of students feel that they have gained a lot from the course and have had a good learning experience. For example, some students said, "Group discussion is more fruitful. We invite the teacher to join

**Table 5.** CT Disposition Quality Difference between Pre-test and Post-test of the Experimental Class ($\alpha$ = 0.01)

| | Pre-test | | Post-test | | Paired *t* test ($\alpha$ = 0.01, df = 39) | |
|---|---|---|---|---|---|---|
| **CT disposition qualities** | **Mean ± SD** | **Range** | **Mean ± SD** | **Range** | ***t*** | ***p*** |
| truth-seeking | 39.43 ± 4.65 | 29–51 | 41.55 ± 6.35 | 24–52 | 2.577 | 0.014 |
| open-mindedness | 45.43 ± 5.54 | 34–56 | 46.78 ± 3.81 | 37–53 | 1.618 | 0.114 |
| analytical tendencies | 45.30 ± 4.51 | 34–53 | 48.08 ± 4.47 | 38–56 | 4.229 | 0.000 |
| systematic tendencies | 39.93 ± 5.22 | 29–51 | 42.23 ± 4.97 | 33–50 | 3.413 | 0.002 |
| CT self-confidence | 40.20 ± 6.31 | 29–53 | 42.73 ± 5.50 | 33–57 | 3.623 | 0.000 |
| inquisitiveness | 48.30 ± 6.69 | 35–60 | 50.58 ± 5.45 | 36–59 | 3.125 | 0.003 |
| cognitive maturity | 44.57 ± 5.43 | 33–55 | 46.00 ± 6.21 | 31–58 | 1.564 | 0.124 |

**Table 6.** Questionnaire on course and the results

| | | | Results (M ± SD) | |
|---|---|---|---|---|
| **No.** | **Questions** | **Scales** | **Exp. Class** | **Con. Class** |
| 1 | What overall grade would you give this course? | 1 = "poor"<br>5 = "excellent" | 4.20 ± 0.69 | 3.91 ± 0.78 |
| 2 | How much work did you have to put in for this course? | 1 = "too much work"<br>5 = "too little work" | 3.02 ± 0.65 | 2.80 ± 0.60 |
| 3 | How well did you feel you learned the course matter? | 1 = "very badly"<br>5 = "very well" | 4.33 ± 0.79 | 4.11 ± 0.67 |
| 4 | How was your learning experience? | 1 = "boring"<br>5 = "fun" | 4.01 ± 0.77 | 3.81 ± 0.73 |
| 5 | How motivating do you feel the group discussion was? | 1 = "not motivating"<br>5 = "very motivating" | 4.27 ± 0.65 | |
| 6 | How much harder did you work than usual? | 1 = "much lazier"<br>5 = "much harder" | 3.61 ± 0.78 | |
| 7 | Give some words to your experiences about the course if possible. | None | – | – |

our WeChat group, and ask the teacher for advice if we do not understand." "Our online and offline discussions are active, and we have gained a lot, broadened our horizons and deepened our learning." "The discussion activity is a kind of cultivation of innovation and comprehensive ability. The teacher follows up on each project carefully and responsibly." "More communication with team members improves teamwork and communication skills." "Although I think the content of the course is very large and often feel stressful, the teacher can always inspire me a lot of thinking." "Group discussions not only trained our oral and written communication skills, but also allowed us to gain friendship." These remarks lead to the conclusion that the PBL learning experience was very positive.

The teaching experiences of the experimental class also gave the instructor a deep impression on online and offline interaction with students. The whole class had a QQ group. Every discussion group had its own QQ or WeChat group. The class QQ group mainly focused on the discussing problems encountered in classroom teaching and students' learning, such as how to understand a concept and how to solve a problem. The QQ or WeChat discussion groups mainly focused on the PBL activities of the group, such as problem selection, literature review, activity coordination, report writing, etc. The Email is also a useful tool for course teaching and learning. The email sent by students mainly involved suggestions on course teaching, confusion and perception in learning, etc. If online interaction were insufficient, the face-to-face conversation or discussion would follow after class. Students can make an appointment and meet the instructor during every week's office hour for more in-depth exchanges of views. The instructor also participated in the group discussion during off-class time. As one member of the discussion, the teacher's participation can not only ensure the normal implementation of discussion activities, but also greatly promote the effect of discussion.

For example, one student in the experimental class found the views about Thevenin's theorem in a published paper was inconsistent with what was learned in class. The student sent an email to the instructor to raise his doubts. After careful analysis, it was found that the viewpoint of this paper was wrong. The instructor then exchanged views with the student face to face in the office, encouraged the student not to blindly believe in authority and to think independently about the causes of contradictory views. Finally, the student gave a correct explanation for the so-called "contradictory phenomenon".

## 4. Discussion

In this research we found that the PBL approach could promote students' CT disposition, but the scores of the seven aspects of CT disposition of the experimental class which were shown in Table 5 showed that among the CT disposition qualities, truth-seeking, open-mindedness and cognitive maturity had no significant difference while analytical tendencies, systematic tendencies, CT self-confidence and inquisitiveness had significant differences between the pre-test and post-test. The possible reasons are as follows:

(1) The qualities of truth-seeking, open-mindedness and cognitive maturity belong to the higher stage in the cognitive development of individuals. These qualities are related to the individual's age, long-term education experience, development level of abstract thinking, and self-esteem development level [37]. Young adults with high self-esteem are also more willing to take responsibility and have a higher sense of control over life and career [38]. According to Piaget's theory, the abstract thinking of individuals does not appear until the age of 11 to 15, but many individuals have not developed to this stage in their lives [39]. Learning experience has a great impact on individual cognitive development. Lisi & Staudt's research found that the abstract thinking ability of college students in tasks related to their professional courses may not have the same performance in other tasks [40]. Sternberg found through his research on college students that the individual's analytical ability is positively correlated with the various challenges accepted in the process of individual growth [41]. It can thus be seen that the higher level of cognitive development cannot be achieved overnight.

(2) The qualities of analytical tendencies, systematic tendencies, CT self-confidence and inquisitiveness can be quickly possessed by short-term cultivation and training. In particular, the seven-step problem solving method itself is a good thinking skill to improve the analytical ability and systematic ability of problem solving. Once this skill is mastered, the problems will be solved according to these steps, which will naturally increase the individual's qualities of analytical tendencies, systematic tendencies, CT self-confidence, and inquisitiveness. As found by Facione, Facione and Sanchez, the level of CT self-confidence is positively correlated with the proficiency of CT skills [42]. Our research results also indicate that the qualities of analytical tendencies, systematic tendencies, CT self-confidence and inquisitiveness can be improved by mastering CT skills.

## 5. Implications

The Implications of this research are as follows:

(1) Sufficient time should be allocated to the implementation of PBL. The group forming stage lasted for three weeks. Students had enough time and possibilities to understand each other in this stage. In this way, members of each group can understand each other well and have the willingness to cooperate altogether, thus laying a good foundation for the group activities. The problem determining stage lasted for four weeks and ended before the eighth week. There are two reasons for this arrangement. One is that the solving of the circuit problems needs prerequisite course knowledge and the fundamental concepts, principles and methods are not covered until midterm. The other is that enough time must be reserved for each group to understand, be familiar with, select, discuss and determine what problem is to be solved. Furthermore, each group could discuss with the instructor to promise the problem to be appropriate for PBL approach in one week. Finally, "seven steps" PBL method was used as an instructional model in this research. "Seven steps" are cores of the PBL approach in which critical thinking ability is possibly nurtured [43]. Two rounds of discussion instead of one are arranged in the "seven steps" of PBL implementation stage to leave more opportunities for students to improve problem solving skills and critical thinking ability.

(2) The PBL process must be conducted carefully by both the teacher and students. The instructor should act as a guide, a facilitator, and an observer and provide flexible learning environments for the students during the PBL treatment. Firstly, the instructor should premeditate to embed the PBL approach into the course teaching, i.e., design PBL teaching steps in which what tasks should be finished and how much time to take. For example, how long will the PBL implementation last? What time of the semester will the PBL process be embedded? etc.

Secondly, the instructor could prepare observation forms in advance to record the process of PBL. There are two types of record forms. One is used to record the performance of students and problems raised during the PBL implementation. The other is for student scribes to record the process of PBL discussion, including the problems discussed, the statements made by members, and the conclusions formed. The instructor can improve the PBL implementation and guide students' learning in the subsequent stages by reading these records.

Thirdly, the instructor should give some instructions for unexpected issues that may occur in the process of PBL implementation. For example, the instructor should provide necessary help when some students find no PBL groups to participate in. When the group members cannot reach consensus during discussion, the instructor should intervene to coordinate the views of the group members. In particular, the instructor should respond as quickly as possible to any problems encountered by PBL groups and always encourage students to think independently and critically.

(3) The instructor should create a comfortable atmosphere for group discussion. This atmosphere should be conducive to students' activities and thinking. For example, during the discussion the instructor may say: "Your idea is new and original, is there any other ones?" "Please think about whether there are solutions to this problem?" "What do you think of your partner's idea?" etc.

(4) Generally, each group evinces different learning quality during the PBL process. Some groups are very devoted to the PBL meeting and discussion while some other groups are not. The instructor should observe the PBL process carefully and continuously, participate in the inefficient groups' discussion, and help the groups to formulate a positive atmosphere for discussion.

## 6. Conclusion

Evidence in this study shows that, after a semester of teaching circuit theory with PBL, the CT disposition scores of students have significantly increased. It may be concluded from this study that the PBL approach can significantly promote the CT disposition of engineering students, and their qualities of analytical tendencies, systematic tendencies, CT self-confidence and inquisitiveness can be improved by mastering CT skills. Students have gained a lot from the course and have had a good learning experience with the PBL-based approach. The students became more active and involved in the course, and their oral and written communication skills have been improved.

However, only the general impact of PBL on engineering students' CT disposition has been observed in this study. As a case study whose results are far from being universal, empirical studies are still needed to assess the impact of PBL on CT disposition in general. Many variables such as sample size, sample type, instruction type, gender, maturity, instrument, nationality, discipline, treatment duration, and group size should be considered for the effects when implementing PBL. Also, the course teaching hours, PBL mode, problem design, etc. may be considered for PBL-based teaching. The influence of PBL on CT disposition is a very complicated process. Every component of PBL such as discussion, brainstorming session, debate session, interaction, reflection, and feedback can stimulate students' meta-cognition and enhance their CT disposition. These should be studied in the future.

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## References

1. N. C. Facione and P. A. Facione, *The California Critical Thinking Skills Test and the National League for Nursing Accreditation Requirement in Critical Thinking*, Millbrae, CA: California Academic Press, pp. 1–2, 1994.
2. V. Suligoj, R. Zavbi and S. Avsec, Interdisciplinary Critical and Design Thinking, *Int. J. of Engineering Education*, **36**(1A), pp. 84–95, 2020.
3. P. A. Facione, *Critical thinking: A statement of expert consensus for purposes of educational assessment and instruction*, Millbrae, CA: California Academic Press, pp. 13–14, 1990.
4. P. A. Facione, *The California Critical Thinking Skills Test – College Leve. Technical Report #1: Experimental Validation and Content Validity*, Millbrae, CA: California Academic Press, p. 4, 1990.
5. P. A. Facione, *Critical Thinking: What It Is and Why It Counts*, San Jose: California Academic Press, 2011.
6. P. A. Facione and N. C. Facione, *The California Critical Thinking Disposition Inventory (CCTDI) Test Administration Manual, Millbrae*, CA: California Academic Press, 1992.
7. C. E. Nelson, Critical thinking and collaborative learning, *New Directions for Teaching and Learning*, **1994**(59), pp. 45–58, 1994.
8. A. A. Gokhale, Collaborative learning enhances critical thinking, *J. of Technology Education*, **7**(1), pp. 22–30, 1995.
9. C. N. Loes and E. T. Pascarella, Collaborative learning and critical thinking: testing the link, *J. of Higher Education*, **88**(5), pp. 726–753, 2017.
10. T. S. Susiani, M. Salimi and R. Hidayah, Research Based Learning (RBL): How to improve critical thinking skills? *Global Conference on Teaching, Assessment, and Learning in Education*, pp. 1–6, 2018.
11. Usmeldi, R. Amini and S. Trisna, The development of research-based learning model with science, environment, technology, and society approaches to improve critical thinking of students, *J. Pendidikan IPA Indonesia*, **6**(2), pp. 318–325, 2017.
12. L. Mason, N. Ariasi and A. Boldrin, Epistemic beliefs in action: Spontaneous reflections about knowledge and knowing during online information searching and their influence on learning, *Learning and Instruction*, **21**(1), pp, 137–151, 2011.
13. H.-C. Kuo, Y.-T. C. Yang, J.-S. Chen, T.-W. Hou and M.-T. Ho, The impact of design thinking PBL robot course on college students' learning motivation and creative thinking, *IEEE Trans. Edu.*, **65**(2), pp. 124–131, 2022.
14. M. A. R. Sapeni and S. Said, The effectiveness of case-based learning in increasing critical thinking of nursing students: A literature review, *Enfermería Clínica*, **30**(S2), pp. 182–185, 2020.
15. T. Harman, B. Bertrand, A. Greer, A. Pettus, J. Jennings, E. Wall-Bassett and O. T. Babatunde, Case-Based Learning facilitates critical thinking in undergraduate nutrition education: students describe the big picture, *J. of the Academy of Nutrition and Dietetics*, **115**(3), pp. 378–388, 2015.
16. D. Saleewong and P. Suwannatthachote, Case-Based Learning on web using questioning techniques and reflective thinking upon critical thinking of undergraduate students' In T. Amiel & B. Wilson (Eds.), *Proceedings of EdMedia 2012: World Conference on Educational Media and Technology*, pp. 992–997, 2012.
17. M. Duran and İ. Dökme, The effect of the inquiry-based learning approach on student's critical-thinking skills, *Eurasia J. of Mathematics, Science & Technology Education*, **12**(12), pp. 2887–2908, 2016.
18. F. Ghaemi and S. J. G. Mirsaeed, The impact of inquiry-based learning approach on critical thinking skill of EFL students, *EFL J.*, **2**(2), pp. 89–102, 2017.
19. A. Masek and S. Yamin, The effect of problem-based learning on critical thinking ability: a theoretical and empirical review, *Int. Review of Social Sciences and Humanities*, **2**(1), pp. 215–221, 2011.
20. Y. Liu and A. Pasztor, Effects of problem-based learning instructional intervention on critical thinking in higher education: A meta-analysis, *Thinking Skills and Creativity*, **45**(9), pp. 1–21. 2022.
21. S. Agdas, *Effects of Problem-Based Learning on Development of Critical Thinking Skills and Dispositions in Engineering*, University of Florida, ProQuest Dissertations Publishing, 2013.
22. C. D. Eren, Effect of problem-based learning (PBL) on critical thinking disposition in science education, *J. of Environmental Protection and Ecology*, **14**(3), pp. 1353–1361, 2013.
23. G. Gunawan, A. Harjono and L. Herayanti, Problem-based learning approach with supported interactive multimedia in physics course: its effects on critical thinking disposition, *J. for the Education of Gifted Young Scientists*, **7**(4), pp. 1075–1089, 2019.
24. D. Pu, J.-H. Ni, D.-M. Song, W.-G. Zhang, Y.-D. Wang, L.-L. Wu, X. Wang and Y. Wang, Influence of critical thinking disposition on the learning efficiency of problem-based learning in undergraduate medical students, *BMC Medical Education*, **19**(1), pp. 1–8, 2019.
25. A. Ahern, C. Dominguez, C. McNally, J. J. O'Sullivan and D. Pedrosa, A literature review of critical thinking in engineering education, *Studies in High. Educ.*, **44**(5), pp. 816–828, 2019.
26. E. D. Graaf and A. Kolmos, Characteristics of Problem-Based Learning, *Int. J. Eng. Ed.*, **19**(5), pp. 657–662, 2003.
27. R. Delisle, *How to Use Problem-Based Learning in the Classroom*. Association for Supervision and Curriculum Development Alexandria, Virginia USA, 1992.
28. L. R. J. Costa, M. Honkala and A. Lehtovuori, Applying the Problem-Based Learning Approach to Teach Elementary Circuit Analysis, *IEEE Trans. Edu.*, **50**(1), pp. 41–48, 2007.
29. J. H. C. Moust, H. J. M. Van Berkel and H. G. Schmidt, Signs of erosion: Reflections on three decades of problem-based learning at Maastricht University, *Higher Education*, **50**(11), pp. 665–683, 2005.

30. J. McMillan, Enhancing college students' critical thinking: A review of studies, *Research in Higher Education,* **26**(3), pp. 3–29. 1987
31. L. S. Behar-Horenstein and L. Niu, Teaching critical thinking skills in higher education: A review of the literature, *J. of College Teaching and Learning*, **8**(2), pp. 25–41. 2011.
32. W. Pan and J. Allison, Exploring Project Based and Problem Based Learning in Environmental Building Education by Integrating Critical Thinking, *International Journal of Engineering Education*, **26**(3), pp. 547–553, 2010.
33. M.-C. Peng, G.-C. Wang, L.-J. Chen, M.-H. Chen and H.-H. Bai, Validity and Reliability of the Chinese Critical Thinking Disposition Inventory, *J. of Nursing*, **39**(9), pp. 644–647, 2004.
34. Y.-M. Hou, Critical Thinking and Its Relevant Factors among Undergraduates, *J. of Edu. Theory and Management*, **5**(2), pp. 23–30, 2021.
35. R.-C. Qiang, Q. Han, Y.-Y. Guo, J. Bai and M. Karwowski, Critical Thinking Disposition and Scientific Creativity: The Mediating Role of Creative Self-Efficacy, *The J. of Creative Behavior*, **54**(1), pp. 90–99, 2018.
36. J. C. Perrenet, P. A. J. Bouhuijs and J. G. M. M. Smits, The Suitability of Problem-based Learning for Engineering Education: Theory and practice, *Teaching in Higher Education*, **5**(3), pp. 345–358, 2000.
37. W. A. Suliman and J. Halabi, Critical thinking, self-esteem, and state anxiety of nursing students, *Nurse Education Today*, **27**(2), pp. 162–168, 2007.
38. L. O. Atac, D. Dirik and H. T. Tetik, Predicting career adaptability through self-esteem and social support: A research on young adults, *Int. J. Educ. Vocat. Guidance*, **18**(1), pp. 45–61, 2018.
39. H. Beilin and G. Fireman, The foundation of Piaget's theories: mental and physical action, *Advances in Child Development and Behavior*, **27**(8), pp. 221–246, 1999.
40. R. D. Lisi and J. Staudt, Individual differences in college students' performance on formal operations tasks, *J. of Applied Developmental Psychology*, **1**(3), pp. 201–208, 1980.
41. R. Sternberg, Applying psychological theories to educational practice, *American Educational Research J.*, **45**(1), pp. 150–165, 2008.
42. N. C. Facione, P. Facione and C. A. Sanchez, Critical thinking disposition as a measure of competent clinical judgment: the development of the California Critical Thinking Disposition Inventory, *J. of Nursing Education*, **33**(8), pp. 345–350, 1994.
43. A. Masek and S. Yamin, The Impact of Instructional Methods on Critical Thinking: A Comparison of Problem-Based Learning and Conventional Approach in Engineering Education, *ISRN Education*, **2012**(1), pp. 1–7, 2012.

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