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Empirical Analysis of Critical Thinking in Electrical Engineering and Computer Science Courses

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Abstract: In teaching and learning, the effectiveness of pedagogies centers around a range of teaching techniques. Adapting the techniques encompasses a comprehensive guide for teachers, structured and whole-class group work, guided learning, assessment practice, and individual activity. Creating a deliberate and effective pedagogy in teaching and learning is a key, ongoing improvement process that helps students learn more effectively and develop high order thinking skills. Various pedagogies can be found in the research articles that have been established for the successful implementation of teaching and learning strategies. Critical Thinking (CT) is a problem-solving pedagogy to make good decisions resulting in appropriate outcomes. In the current work, we use a guided CT pedagogy to apply most of its standards and elements to different science and engineering subjects to improve the targeted outcome of the students' learning. The embedded model was sketched in detail for each subject and analyzed as per the actual outcomes of the targeted objectives.

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1. Introduction

The rapid increase in the availability of different academic resources accessible to students has mainly resulted in twofold outcomes. First, the students can now assimilate more details about the discussion topics, resulting in further clarity. Second, the students may restrict themselves to what's already available without thinking outside the box. If the outcome is latter, the role of Critical Thinking (CT) becomes inevitable. Several studies have been conducted in this regard [2][11][14] that highlight the significance of imparting CT [3] through active learning [7][8]. The studies established that CT in teaching and learning led to more clarity and accuracy in studied and / or taught contents [9].

Similarly, a better outcome was demonstrated in terms of completeness given the assumptions, which should be clearly stated. Moreover, it is worth noting that imparting CT resulted in intellectual integrity, fair-mindedness, and perseverance [1]. In summary, the standards of CT, such as clarity, precision, fairness, depth, relevance, etc., should be applied to CT elements. Some of the CT elements include concepts, assumptions, inferences, questions, and implications. Finally, using CT standards to its

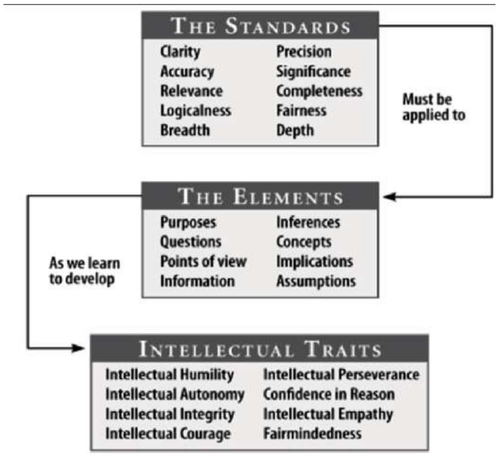

Fig. 1: Paul-Elder Framework for Critical Thinking

elements should develop intellectual traits such as integrity, fair-mindedness, empathy, etc. [12]. Figure 1 shows the overall architecture of the CT model we plan to investigate in the current study.

Numerous attempts have been carried out to incorporate the CT model into different disciplines of teaching and learning [13]. These works can be categorized into multiple sections for the sake of description. The CT model was incorporated and executed in some works but not appropriately assessed [6]. Similarly, the architecture was embedded very well with assessment components in place [15]; however, the lack of quantitative analysis makes it difficult to validate the presented results. It is interesting to observe that the CT model was tested with its standards and elements for different courses, and the quantitative outcome was presented [5]. However, both the elements and the standards were too few to be relied upon regarding the concluding points [4]. Finally, works are available with the complete picture of the proposed study. However, these were not applied to engineering subjects [10].

The application of the CT model is pivotal to science and engineering education since both education categories are based on logical reasoning. Therefore, rigorous analysis of its application and outcome is essential in education. The objectives of the current study can thus be summarized as follows:

- To develop a teaching framework based on the CT model and active learning in an attempt to achieve set objectives.

- To map the set objectives on those of the CT model.

- To analyze the performance of the students through teaching surveys, tutorials, and other assessment techniques.

- To calibrate the objectives, assessment schemes, and teaching strategies considering analytical results.

- To propose an efficient CT model teaching strategy, at least for engineering and computer sciences subjects.

The rest of the paper is organized as stated here. Section II details the CT model, highlighting its key components and its applications in the subsections of the three mentioned courses. These describe how the CT model is integrated into the selected courses, namely Electric Circuit Analysis, Programming for Engineers, and Software Project Management. The next Section III comprises our survey results along with the corresponding analyses. The last section concludes the work and delineates the plans for the future.

2. Critical Thinking Model

The Paul-Elder Critical Thinking (CT) model to be used for the current work is shown in Figure 1. We select this CT model because:

- The course teaches students how to add clarity and accuracy to the technique they plan to use for circuit analysis.

- The course teaches students how to add clarity and accuracy in terms of circuit connections, such as the use of 'reference node' and 'dependent source connections'.

- The course teaches the significance of each technique to be used for circuit analysis.

- The course teaches students the completeness of the work in terms of the given circuit, i.e., missing even a single component (e.g., 'reference node') can lead to significantly wrong analysis.

- Each analysis technique to be taught has a clear purpose and some assumptions. Some fundamental concepts about electrical technology are delivered during the course.

It is to be noted here that we have selected 'clarity' and 'accuracy' as the primary intellectual standards. However, these are not meant to be exclusive of other standards such as 'logic' or 'depth'. In contrast, clarity and accuracy are fundamental standards that serve as the basis for all other critical thinking standards. In other words, logic and depth are ineffective without clarity and accuracy. For instance, if an argument's premises are unclear or incorrect, logic will fail. Likewise, depth cannot be accomplished if the presented information is not clear and accurate. Hence, the other criteria can only be effectively implemented if clarity and accuracy are given top priority.

Another concern is how the quality of reasoning is tested. The Paul-Elder Critical Thinking (CT) paradigm provides a comprehensive framework for assessing the quality of reasoning. This model focuses on the importance of clarity and accuracy in critical thinking and provides a structured method for evaluation of reasoning.

According to Bloom's Taxonomy, the emphasis on clarity and accuracy corresponds to levels 4 and 5 of the higher-order thinking abilities of analysis, synthesis, and evaluation. To master these abilities, one must be able to think critically in challenging situations. The assessment plan for the three given courses includes quizzes, exams, and laboratories that allow students to demonstrate their understanding and application of critical thinking skills. Students' problem-solving methods can be evaluated for clarity and accuracy, as well as their ability to recognize and evaluate assumptions, arguments, and evidence.

Next, we apply this model for at least the below three courses:

A. Circuit Analysis

B. Programming for Engineers

C. Project Management

There are multiple reasons for selecting these courses: Firstly, all these courses are fundamental courses (taught in the first two years) and hence, have common features for our choice. Secondly, all three courses assess students' abilities by targeting a unique and different skill. Circuit Analysis on hardware and analytical skills, whereas programming and logical skills are the focus in Programming for Engineers. Management skill is assessed in Project Management. Therefore, we find it connecting them together to analyze comprehensive critical thinking stemming from these courses. Based on Bloom's taxonomy, this work mainly focuses on application and analysis skills of the students both at the elementary level. The reason for surveying higher-year students is mainly to see how these courses have affected their CT skills. This is because these courses are prerequisites for many courses in the degree program. Finally, although these courses are basic level, they do require basic critical thinking to excel in courses for which these are prerequisites.

Following this, complete details on how we implement the model for these courses are presented.

A. Circuits Analysis course

Learning Objectives

LO1: Teach the students how to identify, formulate, and accurately solve / analyze electrical circuits by applying precise principles of engineering, science, and mathematics. This can be further broken down as follows:

LO1-1: Tell the students about fundamental studies of electrical circuits, and provide them with a platform for identifying nodes, super-nodes, loops, super-meshes, etc.

LO1-2: Tell the students basic laws of circuit analysis to learn analysis and problem-solving skills throughout this course.

LO1-3: Tell the students multiple techniques for circuit analysis and how they can solve / analyze the given circuit by appropriate selection of these techniques.

LO2: Teach the students to conduct appropriate in-depth experimentation, analyze and interpret data, and use engineering judgment to draw conclusions based on stated assumptions. This can be further broken down as follows:

LO2-1: Tell the students to validate the fundamental studies of electrical circuits by wiring circuits physically or in some simulation software.

LO2-2: Tell the students how to analyze and interpret data obtained through physical experimentation or simulation and then how to use engineering judgment to conclude appropriately.

Teaching Strategies

The following strategies are intended to be used in this course:

Experiment-based information: Whatever is taught theoretically will be implemented in the physical lab or some simulation software (QUCS) as it greatly helps students' learning.

Inquiry-based information: The lecture flow will be a function of asking questions about the circuit, such as the following:

- Why is it so…?
- How can we solve…?
- Is there any other way to solve…?
- Why is it not…?

Teamwork: The students are grouped and given a task to solve through discussions.

Assessment Plan

Assessment components include quizzes, mid / terminal exams, labs, class participation quizzes, and submission of group activities. The course contents with all assessment details are given in Table I.

Table 1 : Contents and Assessment Details of Circuit Analysis Course

	Contents	Content-specific objectives	Assessment components
1	Kirchhoff's current and voltage laws	Train the students to accurately analyze electrical linear circuits by applying precise principles of engineering and mathematics Train the students to experimentally validate their theoretical learning using QUCS software and /or troubleshooting in the lab Develop an ability to conduct a comparative study of results obtained both theoretically and experimentally and draw conclusions effectively Train the students how to effectively work in a group during lab sessions	Quiz 1 & 2 Labs1 & 2: Laboratory experiments and / or QUCS Simulation tool to be used Terminal exam
2	Additional analysis	Train the students to accurately analyze electrical linear circuits by more than one	Midterm exam

B. Programming for Engineers course

This course emphasizes solving complicated technological problems by integrating critical thinking and current information. We select the CT model because:

- The course highlights the significance of using computational techniques to address complicated problems in engineering and science.
- The course teaches students how to approach challenges effectively and apply accurate data-processing tools.
- The course teaches students to add clarity in writing a computer program by emphasizing its underlying logic.
- The course teaches students how to add accuracy by analyzing the computational results by identifying the information that the computation should output.
- The course teaches students how to analyze computational results by assessing the impact of overall computational errors on the precision of the results.
- The course teaches students how to report computational results in a complete and accurate format.

Learning Objectives

LO1: Be familiar with the fundamentals of computer programming and understand the need for computational problem solving.

LO2: Improve algorithmic thinking skills and apply them to engineering problem-solving through pseudocode, flowcharts, and writing programs.

LO3: Be familiar with C++ basics to develop good programming practice with coding styles and debugging skills.

LO4: Apply sub-tasking techniques to solve more extensive problems and write modular C++ programs with functions.

LO5: Implement and run computer programs for engineering problem-solving using the available software.

Teaching Strategies

The following strategies are used in this course:

Direct Instruction: explicitly convey information and develop skills in students involving sequential steps.

Experiential Learning: Hands-on programming practice in the computer lab to put what students learn into practice by giving them problem-solving exercises critical to their success in the classroom.

Inquiry-based information: Students are guided through inquiry-based learning, which involves posing questions, devising techniques, and analyzing the results. Investigating helps students find evidence to back up their theories and hypotheses.

Teamwork: The students are grouped and given a task to solve through discussions.

Assessment Plan

Assessment components include quizzes, mid / terminal exams, labs, class participation, and group activities submission. The course contents with all assessment details are given in Table II.

C. Project Management course

This course deals with processes, tools, techniques, and skills relevant to managing projects in the field of Information Technology.

Starting with an overview of project management, various aspects involved in handling projects are covered. The software development life cycle (SDLC) stages, viz., requirements specifications, design, development, testing, and maintenance, are illustrated along with scope analysis, feasibility study, estimation, and scheduling.

The students also learn relevant topics such as human resource allocation, role-playing, leadership, communication, quality assurance, ethics, and risk management. The challenges in managing projects are elaborated with case studies.

Learning Objectives

The objectives of this course are stated below:

LO1: To learn basic principles of IT project management.

LO2: To conduct a feasibility study for projects.

LO3: To schedule the tasks in a project and mobilize resources.

LO4: To handle different modes of communication and work in a team.

LO5: To monitor the deadlines and track the execution.

LO6: To identify risks and avert any potential pitfalls.

LO7: To practice project management concepts in real-world scenarios.

LO8: To keep abreast with Project Management Professional certification.

The learning outcomes below ensure that on successfully completing the course, students will be able to:

1. Elicit the requirements aligned with the business strategy.

2. Understand the economic, legal, technical, and operational feasibility.

3. Assign the appropriate resources for completing the project.

4. Choose the suitable communication mode conducive to the team's environment.

5. Schedule a project on the Gantt chart and estimate the costs.

6. Deal with emergent issues and manage consequent risks.

7. Report timely with documentation and ensure maintainability.

Teaching Strategies

The following approaches are adopted for the delivery of this course.

Lecture sessions: the focus is on teaching the concepts using real-world examples. Appropriate aspects are chosen to illustrate contextual frameworks. The course comprises a semester-long running example project covered in phases and different smaller case studies. The lectures are instructor-led and are delivered two hours weekly.

Practice sessions: the students are provided with brief problem scenarios and expected to work in small teams.

Relevant questions are also posed to motivate students to ponder potential issues. The team members actively manage parts of a project and report on the case study. Though these sessions are student-centric, the instructor's guidance is essential to remain focused on systematically adhering to the processes.

Assessment Plan

Continuous assessment throughout the semester includes quizzes, midterm exams, practical tests, and a course project (series of case studies). At the end of the semester, a final exam comprising a variety of questions with sufficient coverage of contents is conducted. The course contents with all assessment details are given in Table III.

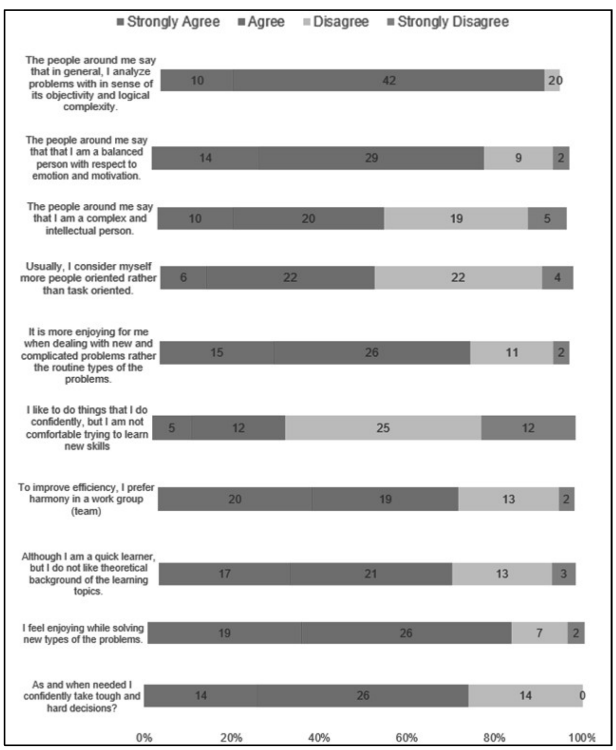

Fig. 2: A self-reflection on problem-solving ability

3. Survey Results and Analysis

It is worth mentioning that the vital attributes of the 21st-century mindset are critical reflection, empirical reasoning, collective intelligence, and metacognition. Therefore, today's students' key skills are critical thinking coupled with problem-solving, creativity with innovation, and collaboration with communication. Measuring the acquisition of such skills is a difficult process. To assess directly, one needs an explicit and complex experimental setup. However, in our courses, we attempt to provide a learning environment for students to develop problem-solving and critical-thinking skills. Therefore, to analyze how the students perceive problem-solving oriented strategies and critical thinking models, two surveys were thoughtfully framed through questionnaires and distributed amongst students of all three courses mentioned above. The first survey is related to problem-solving skills, while the second survey is about CT.

We have incorporated problem-solving and critical thinking abilities in the courses offered, as stated in this paper. The assessment of introducing these pedagogical paradigms was quantified with the rigorous surveys conducted on a wide variety of student populations. In the absence of a baseline model to compare the results, we intend to continue improving the process and assessing the outcomes over the years. We noticed that the grades scored by the students in each of the three courses increased in comparison with the previous year when this model was not implemented.

An observation regarding the assignments in the selected courses is that the evaluation varies from course to course. While the circuit analysis course involves objective assessment, the project management course is relatively subjective. The programming course is intermediate, as there are many possible solutions to a given problem. Judging the optimality of a solution would be a higher level of assessment.

The key results for lower student participation is the general reluctance of students towards different types of surveys. By and large, the students have shown less inclination towards survey participation. The survey presented in this paper was collected after many attempts.

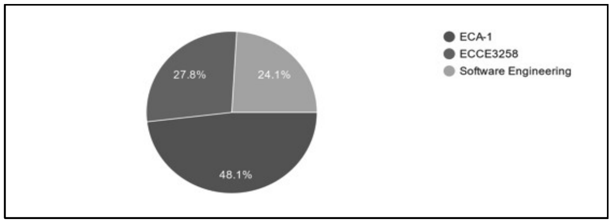

Fig. 3: A Course-wise distribution of students' participation

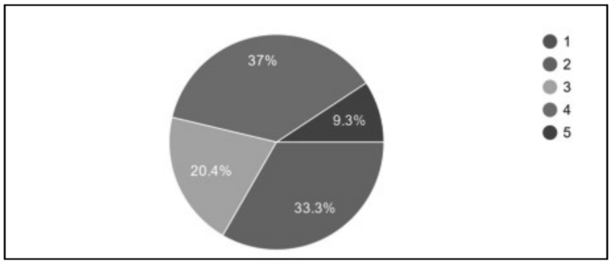

Fig. 4: Study year-wise distribution of students' participation

In the following subsections, we present the results with corresponding analyses of these survey results.

A. Survey of problem-solving ability

The survey results about the problem-solving skills of the students are interesting. Figure 2 shows a balanced split between those who agree with their problem-solving skills and those who do not, by and

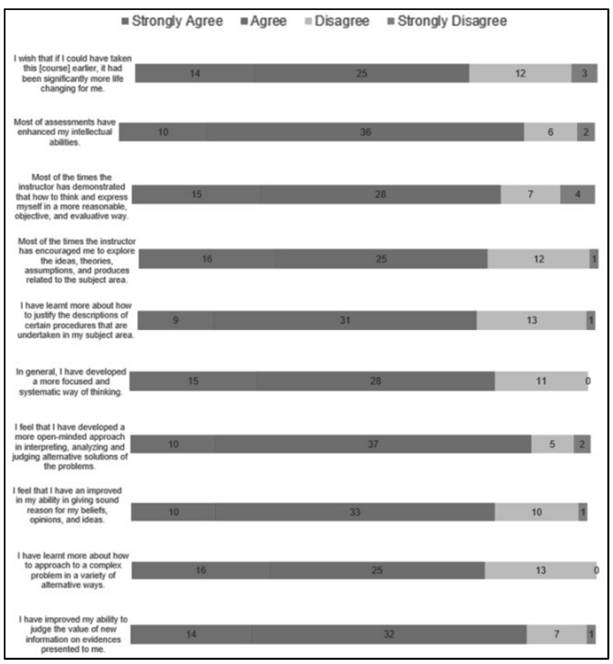

Fig. 5: A self-reflection on critical thinking ability

Table 2. Contents and Assessment Details of Programming For Engineers Course

	Contents	Content-specific objectives	Assessment components
1	Fundamental of computer science terminology and concepts	Describe an architecture and organization of computer hardware components, including the CPU, RAM, and peripherals, including auxiliary storage devices (e.g., hard disks, DVD drives) Identify the primary types of computer software. Explain what an operating system is and why it is so important. Explain the differences between assemblers, compilers, and interpreters as three different categories of translators. Train the students how to effectively work in a group during lab sessions	
2	Problem solving Techniques	Train the students to specify and analyze the problem requirements and develop algorithm and solution methods using	Quiz-1

Table 3. Contents and Assessment Details of Software Project Management Course

	Contents	Content-specific objectives	Assessment components
1	Project management framework	Basics of managing projects in the context of software development	
2	System view of project management	Understanding organizational needs, dealing with SDLC phases	Case study 1
3	Strategic planning and integration	Learning project integration management, developing a plan, performing integrated change control	
4	Project scope management	Executing a requirements plan, defining the scope, creating a work breakdown structure	Quiz 1
5	Time management	Planning schedules, defining and sequencing activities, estimating resources and durations, developing critical path methods	Case study 2
6	Cost management	Understanding the importance of cost and Midterm exam economics, planning and estimating the costs, controlling the budgeted expenditure	

large. It is good to see that the students who strongly disagree with most statements are pretty low, showing that the techniques adopted to inculcate problem-solving skills have played a pivotal role in students' academic lives. This result indicates concern regarding an essential aspect of the student's problem-solving abilities: their willingness to acquire new skills. Most students struggle to recognize their quick learning abilities. On the other hand, it is encouraging to observe that the majority of students are adept at making tough decisions when confronted with difficult circumstances.

Figure 3 shows the course-wise percentage of the student's participation. It is important to highlight that a reasonable number of students have contributed to the survey outcome, thus making it more reliable and independent of the course contents. Moreover, we disseminated the survey amongst post-foundation students of all four-year study, i.e., freshman, sophomore, junior, and senior, as evident from Figure 4. It should be noted that in Oman, the first year is considered the foundation year, usually excluded in many universities across the world. This is why the survey does not take their input into consideration. It also implies that the results may vary from what is demonstrated in Figure 2 in case students from a specific year are selected. The current work can be extended to study this effect in future works.

B. Survey of critical thinking ability

Figure 5 shows survey results on the critical thinking ability of the same students who gave feedback on problem-solving skills. It is important to highlight that all the critical thinking objectives targeted in the survey are satisfactorily achieved, as evident from a much higher percentage (>75%) of the students who agree or strongly agree than those who do not. Moreover, the results also show that 80% or more students are convinced of different strategies adopted by their respective instructors to incorporate cognitive skills. This can be verified through the survey results of questions 2, 3, 5 to 8, and 10 shown in Figure 5. As a feedback mechanism for future cognitive teaching strategies, what needs to be focused on is enhancing the students' abilities to identify and solve complex problems (questions 4 and 9 results). It is suggested to expose students rigorously to complex problems by asking them to identify these first, then encouraging them to think of their solutions.

4. Conclusions And Future Work

In this article, we have demonstrated the use of a critical model for three courses linked with different disciplines. The modeling details of all the courses were presented mainly in terms of course objectives, contents, assessment components, and delivery plans. Three different instructors successfully taught the developed model at different institutes, followed by its assessment through a rigorous survey.

The survey results have shown satisfactory implementation of the model in terms of good gain in students' cognitive skills, content delivery, challenging their curiosity, etc. However, it has been brought to light that further work is required in certain areas to achieve the stipulated objectives; some suggestions were discussed in the previous section. The future work includes improvement in the design such that all the objectives can be achieved in the best way possible.

It would further be insightful and thought-provoking to compare the results in terms of improvement in overall student performance. We shall continue assessing the proposed techniques over a longer period and record the observations accordingly. Since the experiment was voluntarily set up, the course assessment was not revamped. The focus of the current work was to introduce CT pedagogy, highlight its theoretical strengths, and how it can be applicable to different subjects. The work also includes student's feedback when these different pedagogies are applied. As far as the impact study is concerned, that is beyond the scope of this present work, mainly because of the time it requires to be carried out in order that one could have stable results. However, we have this in mind for our future work to consolidate the current work.

This research will certainly form the basis of rubric enhancement to evaluate the students' clarity and accuracy. Perhaps a psychometric kind of test tuned to engineering aspects would need to be developed for this purpose in the future.

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