Critical Thinking Development in Physics Courses by Problem-Based Learning in Virtual Collaboration Environments

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Abstract

This research comprises the design of a strategy to develop critical thinking skills throughout physics courses in engineering degrees through collaborative work, problem-based learning (PBL), and virtual classroom interactions. To know the level of student development, an evaluation instrument is applied. The results allow us to propose improvements in learning strategies, achieving greater learning effectiveness before the end of the course. Various research stages use quantitative, qualitative, and inductive-deductive methods. An open-ended question instrument is adapted to show the students' initial and final critical thinking skills. This didactic instrument focuses on developing critical thinking through the use of collaborative work to solve problems in virtual classrooms. We find that students demonstrate cognitive skills that allow them to find the right solutions based on analysis and inference with various proceedings.

1. Introduction

Due to the lockdowns during the COVID-19 pandemic, learning problems appeared; memorization and repetition are no longer effective in achieving the expected educational results in physics courses, where problem-solving skills are required. It is urgent to implement strategies to develop 21st century skills that favour the learning process (Ennis, 1995; Slisko, 2017). Online resources developed during lockdowns are used for the benefit of teaching and learning processes (Alsaleh, 2020).

There is a strong interest in incorporating Critical Thinking (CT) in education. CT is analysed through understanding and situational analysis, with strategies that promote thinking as the basis for generating knowledge. (Alsaleh, 2020). There is a disposition of educators to motivate their students to be critical of the decisions and situations fostered by government policies.

Additionally, international organizations have noted that the development of CT has a significant impact on how people understand and solve problems (OECD, 2018; UNESCO, 2022). Nowadays, industries and large corporations give importance to hiring leaders who can observe, analyse, argue, and make assertive decisions. Good leaders tend to self-evaluate their own experiences to learn and become experts in their field. Taking the perspective of Paul (1993), one must be able to inquire about a topic from multiple perspectives and develop both disposition and the ability to be self-critical (Ralston & Bays, 2015; Higgins, Frankland, & Rathner, 2021).

Focusing our attention on the formation of engineers in the field of computing science, quoting ABET (2023), "Engineering design is a process of creating solutions to problems by using science, math, and engineering principles. It is an iterative process, meaning that it involves repeating steps as needed to improve the solution". Thus, didactic strategies must develop collaborative work and critical thinking skills alongside the knowledge required in engineering from the first semesters.

With the recent lockdowns due to the COVID-19 pandemic, it became evident that many educational institutions need to promote collaborative skills and critical thinking. Teamwork is sometimes misunderstood as the division of tasks among the most capable people so that only some members of the team solve problems. Simultaneously, collaboration and negotiation between peers is made difficult due to the lack of soft skills necessary for collaborative work. Specifically, at the Escuela Superior de Cómputo (ESCOM) of the Instituto Politécnico Nacional (IPN), a survey was carried out on the experience of working in class (Hiscox, Papakonstantinou, & Rayner, 2022). The results showed a preference for individual work since most classes require students to work alone with a computer and almost no interaction with others.

So how do you encourage student interaction to improve their interpersonal skills? How are students motivated to develop critical thinking in physics class? To answer, we analysed group interaction in the physics course, where a strategy based on collaborative work (CW) and problem-based learning was implemented through a learning management system (LMS) (Donnelly, 2010).

1.1. Critical Thinking skills

Facione (1990) defines six basic CT skills: interpretation, analysis, inference, evaluation, explanation, and self-regulation. According to Cangalaya (2020), critical thinking skills can be developed by participating in research – stating a hypothesis or position about the work in question. This ability involves investigating, analysing, and selecting information that allows a deeper understanding of a topic. Hence, students find alternative solutions to a problem or solve exercises and answer questions.

Some researchers have investigated the benefits of developing Critical Thinking skills in university physics courses. Aznar and Laiton (2017) obtained results that show the utility of developing basic CT skills in physics class. In a study by Poveda (2014), the proposed solution to problem-solving limitations on students during physics courses included CT elements in work schedules. In the work carried out in the computer systems engineering (ISC, for its Spanish acronym) of the School of Computing proposes a flexible strategy to the different styles of learning, and standardized templates are presented, allowing each teacher to freely adjust it to their subject.

2. Methods and instruments

Quantitative, qualitative, and inductive-deductive methods are used in this research. An open-ended question instrument is adapted to show students' initial and final critical thinking skills. This didactic instrument focuses on knowing the development of CT through collaborative work to solve problems. Most of the peer interaction occurs through the Learning Management System (LMS), such as Google Classroom or a similar platform. This space is used simultaneously to observe the performance and participation of each student in every exercise. Information is collected using checklists and a semi-structured interview to recognize the developed cognitive skills. Lastly, an individual summative evaluation is applied to assess their effectiveness at problem-solving (Ossa et al., 2017). The focus is on observing and analysing the changes in the argumentation before and after applying collaborative work and PBL.

The quantitative instruments are based on the work of Facione (1994), Álvarez (2013), and Alsaleh (2020) about critical thinking through argumentation. A problem observed in the ISC students is misinterpreting text and the need for more certainty in their arguments to support solutions. A documentary analysis of student advancement was performed using rubrics, classifying learning into four levels of achievement (strong, acceptable, weak, and unacceptable).

The inductive-deductive method is an effective way of promoting active learning, critical thinking, and problem-solving skills. This approach was considered during the design of activities because it encourages participation, helps connect new information with prior knowledge, facilitates making observations, drawing conclusions, and applying knowledge in practical situations.

Based on the work of Tiruneh, De Cock, Weldeslassie, Elen, and Janssen (2017), to compare skills development the teacher applied similar tests before and after the collaborative work. The instrument consists of ten questions, six related to concepts, principles, and laws, one to interpret the meaning of the equation, and three to apply the knowledge to solve a basic exercise. The second instrument is very similar to the first, with "question reformulation" or "rephrasing" variations. In this process, the structure or wording of the original question is modified without altering its fundamental meaning. The objective is to present the question differently to identify an improvement in understanding and avoid memorizing specific answers based solely on the original formulation.

2.1 Problem Based Learning (PBL)

In various engineering courses, the most requested competencies are related to problem-solving. Consequently, activities that foster these skills must be considered in didactic planning. According to Rodríguez and Fernández (2016), group work and collaborative learning greatly impact education. In order to develop their skills, the student must discuss, compare, and use their knowledge. These actions will be highly valued in future performance. These authors also mention that class time is insufficient to work on these skills, so self-learning time is required. In addition, Pulido Gómez (2019) affirms that knowledge can be achieved through teamwork due to the social interaction between a collaborative group of people who present and prove their arguments.

2.1.1 The implemented PBL model

The ESCOM physics course lasts 18 weeks. A problem designed to develop critical thinking skills is solved every two weeks – once in a face-to-face session and the next in LMS until the end of the semester. The prior knowledge and the knowledge acquired in the lecture cl (Lectures are typically one-way, with the instructor talking and the students listening) are not homogeneous. However, collaborative work allows exchange and reinforcement of knowledge among team members. All the material used in the class can be reviewed again in the LMS (Ramirez, 2021).

The exercises have low complexity; however, they require the six basic skills of the CT to solve them. Furthermore, following the research of Barrows (1996), students should be able to determine for themselves what to learn and from which resources, guided by the facilitator or tutor. Figure 1 shows the steps to implement PBL in the class. At the same time, collaborative work is used through the division of tasks, discussion, and sharing of knowledge. Students share different perspectives and propose solutions. They analyse the problem collectively, offer explanations and support the understanding of others.

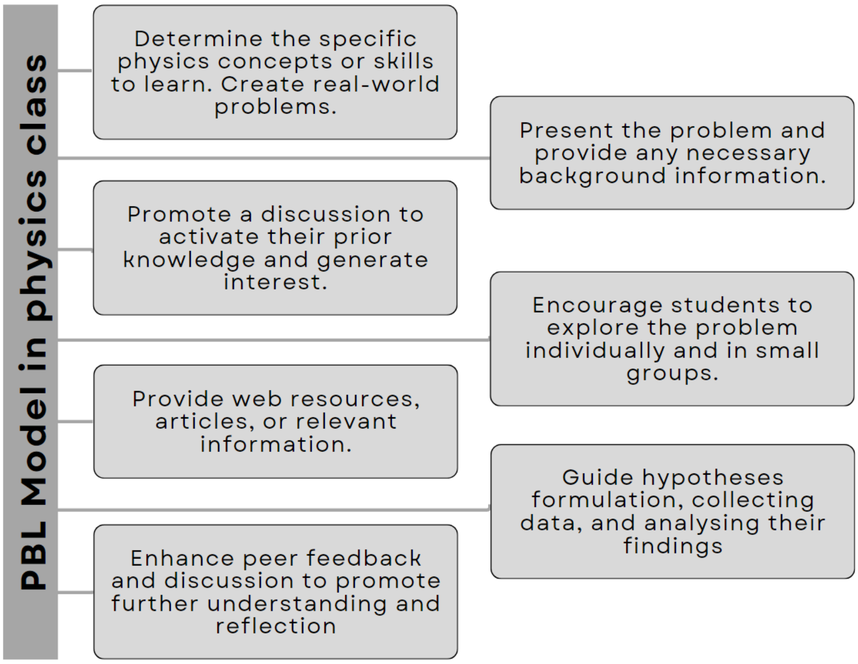

Figure 1. PBL Model

Specifically, at this stage of the process, three types of evidence must be presented by the work teams: the discussion audio, a free-format visual aid (graphic organizer, infographic, slides, posters, or other) with the synthesis of the research and solution, including equations and data that support the results. These evidences provide information on the conceptual and procedural development of the group.

To measure the results, we use an interaction rubric while executing the work proposal and conduct a pre and post-test. The construction of these instruments is based on previous work by other authors referenced in this document. The instruments were validated by five experts in the area and 12 students of excellence from the institution.

In addition, the teacher should promote analysing and solving problems in collaborative environments. As, this practice is expected to be repeated in other activities as the student adapts to the work dynamics.

2.1.2 The application

The dynamics for a class working through the strategy are discussed below. Figure 2 shows an example of a kinematics problem, specifically a Uniform Linear Motion (ULM) problem.

Initially, each team establishes a hypothesis to arrive at their answer. Consequently, the answer can be justified using different procedures. Students can recreate the situation, although the instructions stipulate that there must be a mathematical backing. It is expected that they will be able to use the equations that describe uniform linear motion. The established rules force all students to participate since their participation is related to grades. In the same way, they should look for reliable sources, or material published in the LMS. Thus, they improve their knowledge, study habits, and soft communication skills.

As students become familiar with the strategies, the complexity of the problems increases, and new tasks are performed. These activities complement the information to solve the problem. For example, a set of questions inspired by the Force Concept Inventory (Stoen, McDaniel, Frey, Hynes, & Cahill, 2020) is used to motivate students to find relationships between concepts, laws, and phenomena. However, unlike the other instruments, the questions still need to be validated by experts and advanced students who can confirm that they have a unique solution and that the scenario is correct. This aspect will be addressed in future work. For now, questions serve as a reference to encourage teams to engage in discussion and analysis.

An ESCOM student lowers his stress level while walking. He coordinates his steps with the rhythm of a song that lasts 3 min 14 sec. At the start, the pedometer marks 903 m and 1522 steps. At the finish mark, 1.12 km and 1865 steps. Was the song slow-paced or fast-paced? Make the necessary calculations to answer the question with arguments.
Choose the hypotheses appropriately.

Figure 2. Example of problem sentence to the Lineal Movement

2.2 Virtual collaboration environment using Learning Management System (LMS)

A virtual collaboration environment is a digital platform that enables individuals or teams to work together remotely, sharing information, communicating, and collaborating on projects and tasks. Revelo-Sánchez (2018) concludes that collaborative work as a didactic strategy for teaching/learning programming is an important research theme in the computational and educational fields, given its possible application to increase the learning benefits to students with great technical knowledge On the other hand, Couoh Novelo (2021) inferred that university students working in Virtual Collaboration Environments have better effectiveness and interaction results than students who only work and learn on campus. In this case, the teacher uses a commercial LMS to concentrate and publish information to document the work of the students outside of class. It is also the main repository of evidence for the activity.

2.3 Data collection instruments

The information collected in the session is analysed qualitatively, categorizing it via the system shown in Table 1 and quantitatively using rubrics to evaluate each category.

Table 1. Category system for qualitative analysis of team interactions

Category	*Description*
Relevant data	It is extracted from meeting records, interview transcripts, field observations, and material that provides information about team interactions.
Identification of patterns	Examine the collected data and look for common themes or emerging patterns.
Data coding	According to the identified patterns, the relevant snippets are tagged and classified to organize and analyse the data systematically.
Analysis and interpretation	Explore the different categories to understand the dynamics of team interactions. Looks for connections, trends, or discrepancies that may reveal areas for

	improvement in collaboration among participants.
Data triangulation	Multiple sources and data from interviews and observations are considered to get a more complete and accurate picture of team interactions.
Drawing conclusions	Based on the analysis and interpretation of the information, improvement is identified in the six steps of the TC.

Adapted from Sampieri (2018).

2.4 Rubrics

The rubric used in this work (see Appendix 1) consists of a predefined set of criteria and performance levels that help determine the achievement reached. Rubrics are used to assess student work because they help establish evaluation standards, ensuring fairness and objectivity in evaluating specific CT skills, knowledge, and criteria relevant to the proposal. The rubric is an adaptation of The Holistic Critical Thinking Scoring Rubric (HCTSR) used to assess the quality of thinking displayed in verbal and written presentations. (Facione, 1994; Alsaleh 2020).

3. Participants and Procedure

Participants in this study included 160 first-semester engineering students divided into teams of five people. This sample was selected by convenience, and twenty-five students were in the control group. The course is face-to-face, although the time dedicated to working on this proposal was complemented with hours in virtual mode through the LMS. The academic program specifies 15 hours of face-to-face classes to teach the content and three hours of self-study (ST) to work on exercises and activities to reinforce knowledge. Our strategy used one hour every two weeks to implement the activities designed to develop critical thinking through collaborative work in video call.

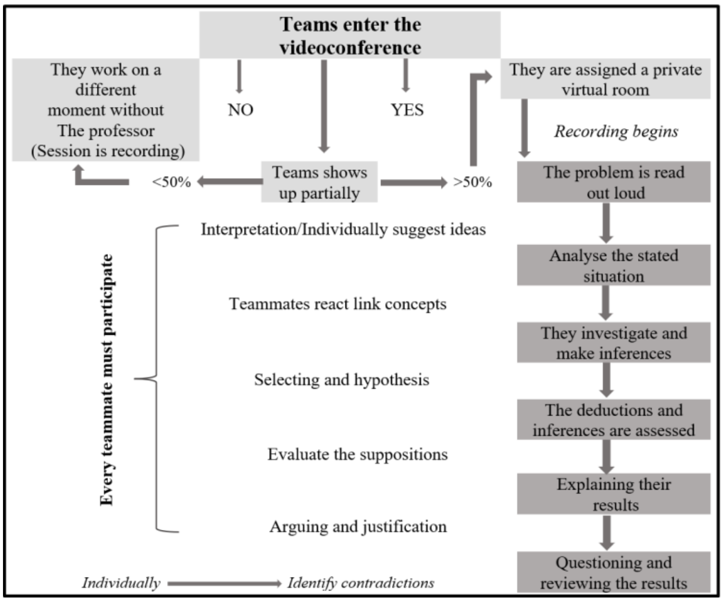

Figure 3. Work sequence during the video call

Figure 3 shows the work sequence of the session. Previously, the teacher confirmed that all students have the resources to access the internet and a computer or device to connect to a video call. The number of attendees was always greater than 80% of the class size. The activity would have been rescheduled if the attendance had been less than 50%.

Table 2 shows the steps included in the work dynamics. The intervention of the teacher is only to clarify concepts or instructions of the activity. When students consider possible answers, it is important for students to draw from both their previous and newly acquired knowledge. In due time, as the students engage in PBL and CW activities, they are expected to tackle problems and present arguments that show their CT progress.

Table 2. Standard procedure for each session

Group Instructions	Phases			Integration
	1st	2nd	3rd	
The teacher explains the work dynamics of each session, and a leader is assigned, preferably on a rotating basis.	The students follow the work dynamic (Figure 3).	The team distributes tasks to condense information and transfers it to their visual aid.	The team presents and justifies their results in front of the group.	The teacher corrects, enriches the knowledge, and synthesizes the information to close the session.

Note 1: The control group (C) performs the same activity as the experimental group but as homework (Figure 2). So, each team in C is free to coordinate their work. Group C must follow the instructions to solve the problem and publish the results through the LMS. All groups must present their results and arguments on slides and then explain them to the class.

4. Results

4.1 Quantitative CT skills evidence

Scores are assigned to each rubric level and the total scores of each participant are obtained. Quantitative performance measurement is necessary to find significant individual and group differences, patterns, and trends. The mean, median and standard deviation are calculated to find out the overall performance of the participants. The scale is standardized, so the student interprets the value obtained. If a student is in the "acceptable column" they have 28 points, which equals 10. If a student scores 12, that equals 4.3. A low score indicates that the student needs to improve their performance.

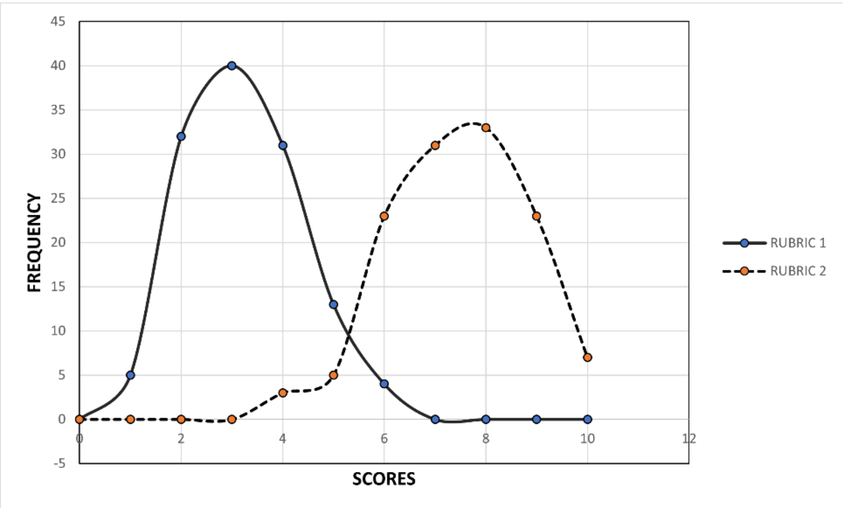

Figure 4. Rubric scores. First and last session of the semester

Figure 4 shows the distribution of rubric scores in the first strategy implementation. The solid line indicates the scores obtained during the initial session, while the dashed line represents the scores from the final session. The x-axis displays the scores, and the y-axis shows how often these grades were given in the sample. Evidently, there was an improvement in the performance of the students between the first and final session. However, more tests are required to know whether this result was impacted by factors unrelated to the CW proposal. For example, at the beginning of the semester, students needed to learn the work strategy and they did not know their team members. At the end of the semester, they already recognize each team member's dynamics and strengths and weaknesses.

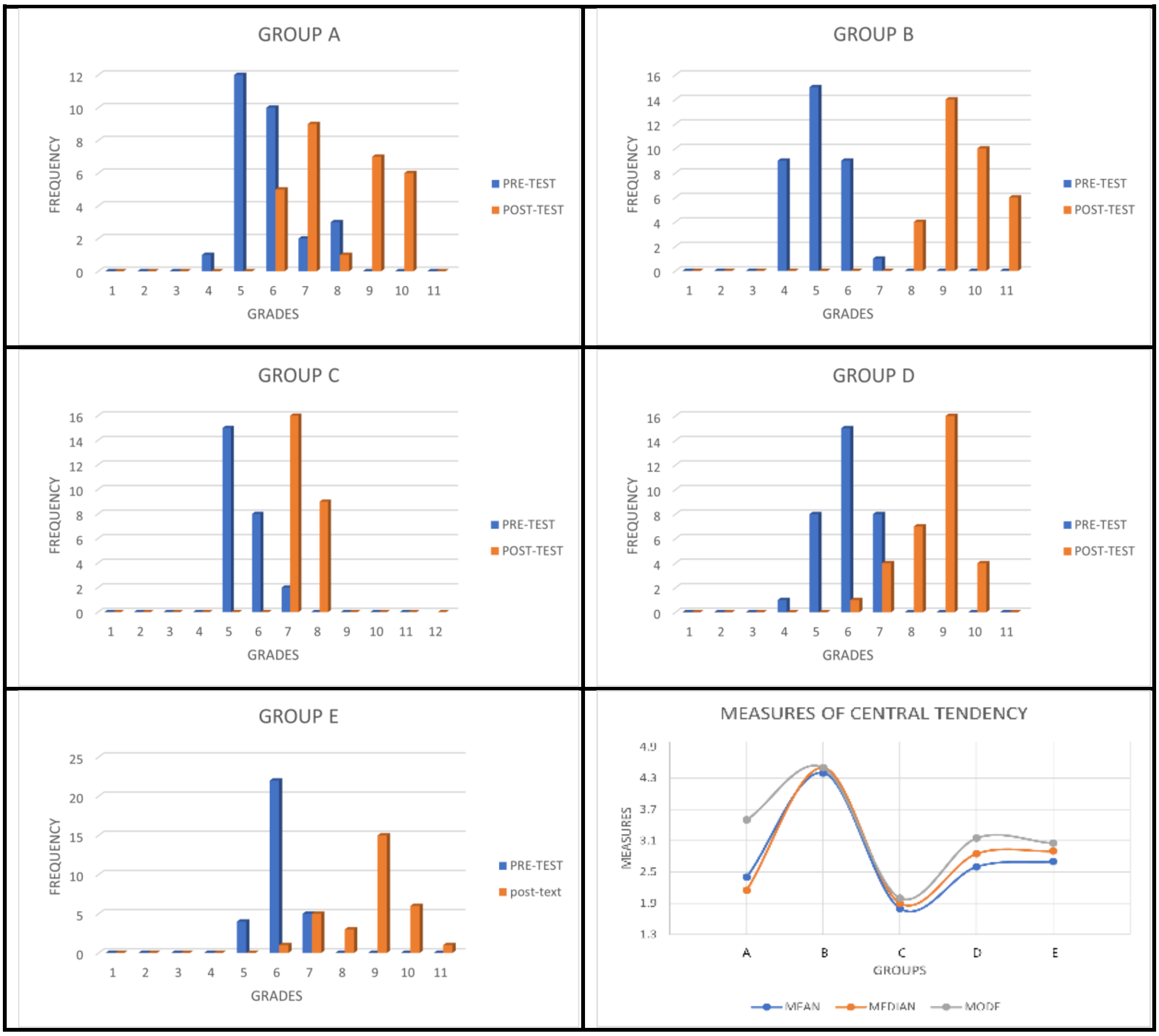

Figure 5. Grades: Pre-test and post-test results

In Figure 5, the progress of the students is analysed by comparing the grades obtained on the second test minus the grades from the first test. A wider gap between the results indicates that the student moved from lower-scoring rubric columns to some higher ones (See Appendix 1). These findings are consistent with the results of the activities, where the assessment of exercises based on rubrics shows that knowledge improved as the strategy is repeated. The graph of measures of central tendency shows that the control group C does not present variation. Something similar happened with the upper grades of group B, which showed a good disposition for collaborative work and commitment to carrying out the activities.

The performance improvement results after applying the strategy are presented in Table 3 and compared with those of the control group. The average scores of the group show a significant increase once ABP was applied, indicating the development of critical thinking skills. Similarly, in the case of exercise resolution and conceptual understanding in the final test, improvement is observed. There is a percentage development of skills according to rubric than of knowledge according to the tests, however, there is growth in both.

Table 3. Quantitative results of groups CW-PBL-LMS

Method	Objectives	Variables	Indicator	Instrument	Average Score Change *
CW-PBL	Develop Critical Thinking through collaborative work and PBL	Studying habits	Assessment scores	Rubric	Group A: 40 % Group B: 38 % Group D: 46 % Group E: 47 %
		Previous knowledge	Level of knowledge	Pre-test Post- test	Group A: 24% Group B: 44% Group D: 26% Group E: 27%
Instructio-nal Model (Spector, 2002)	Enhance the learning process for students	Grades	Level of knowledge	Pre-test Post- test	Group C: 18%

Note: The instructional model focuses on teacher-directed instruction. The teacher plays a central role in delivering content and facilitating learning. Collaborative learning focuses on collaboration among students. The emphasis is on teamwork, social interaction, and knowledge exchange among participants. * A comparative analysis is performed of the average grades of the same group, between the score obtained at the end of the instructional class (Pre-test), and the score after the methodology was applied (Post-test.)

Finally, at the end of the semester, it was revealed that groups A, B, D, and E achieved slightly higher scores compared to the control group (C). This issue and the interpretation of central measures will be discussed in future papers. It is necessary to extract and classify the patterns in the audio to complement the information and find the relationship with the development of CT.

4.2 Qualitative CT skills evidence

In the first three sessions, the students remained well below the maximum (strong) level of performance. In the last two sessions, the majority of performance was between strong and acceptable. Although the change may be due to multiple aspects, the soft skills related to CT are evident. In future work, the patterns, and contrasts between the first and last sessions will be analysed in more depth. Through analysing written tests, interviews, and observations, it has been determined that the student has acquired or improved critical thinking skills by successfully completing most or many tasks listed in the acceptable column, according to Alsaleh (2020).

Notably, students are becoming more accustomed to using CT skills, which may eventually become a habit. Additionally, students develop new skills by actively participating and providing well-informed responses. While their level of progress has yet to be measured with certainty, qualitative evidence shows that they apply CT skills to problem-solving.

The development of confidence and soft skills can be multifactorial. For example, students may become comfortable with their classmates and the teacher as the semester progresses.
Furthermore, at the beginning of the semester, only a few students gave a justified solution to

their procedures. At the end of the course, most of the students solved their problems from a hypothesis (showing their understanding and ability to link information). In some cases, they deduce multiple solutions, and their arguments are based on the new knowledge they acquired during the phases of collaborative work.

During the middle of the semester, students in A, B, D, and E take the initiative to apply problem-solving strategies to other classroom activities. From then on, they do a previous analysis in order to solve and explain the obtained result. Group C solves the problem as a team homework activity. There are no recordings or monitoring of the activity during its development. Only a pre-test is applied after the teacher's explanation, and a post-test after presenting the task results in front of the group.

The students are showing increased participation in class and improved teamwork. They are also demonstrating greater efficiency in conducting research and synthesizing information. Additionally, their ability to comprehend and solve exercises in the textbook has improved.

5. Conclusions

Implementing a strategy centred on developing critical thinking skills through collaborative work and problem-based learning led to a significant improvement in the performance of students and knowledge acquisition.

Before collaborative work, student solutions to tasks presented inconsistencies and misunderstandings of the statement or applied knowledge. However, after implementing the strategy, the students improved their procedures and were able to provide stronger arguments to support their results. Their arguments became clearer and more focused once the strategy was put into action.

A considerable increase was observed in the willingness of the students to justify their results, in addition to greater participation in group classes.

The team demonstrated improved efficiency in investigating and synthesizing information, as well as a greater ability to understand and solve the exercises in the book.

Finally, this study has some limitations that need to be mentioned. First, we work with a convenience sample, which represents 30% of the total population per semester, so it can be considered representative of the population. Next, there is still analysis work to be done with all the information obtained in audio and writing evidence that can shed light on how critical thinking development impacts knowledge acquisition.

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Appendix 1.

Rubric to evaluate student work.

CATEGORY	4 STRONG	3 ACCEPTABLE	2 UNACCEPTABLE	1 SIGNIFICANTLY WEAK
Statement interpretation	The student shows a full understanding of the statement.	The student shows a good understanding of the statement.	The student shows a partial understanding of the theme.	The student may misunderstand the statement.
Analyse	The student can precisely relate every concept and previous or current knowledge englobed by the problem.	The student can precisely relate most of the concepts and previous or current knowledge englobed by the problem.	The student can relate some concepts and previous or current knowledge englobed by the problem.	The student needs help to relate most concepts or knowledge englobed by the problem.
Conceptualization	The student can answer all the questions posed by their classmates with precision.	The student can answer most of the questions posed by their classmates with precision.	The student can answer some of the questions posed by their classmates.	The student cannot answer the questions posed by their classmates.
Investigation	Students consult various sites and extract only useful and reliable information to solve the problem.	Students consult one or two sources and extract only useful and reliable information to solve the problem.	Students consult one or two sources and extract useful information to solve the problem.	Students consult one or more sources but do not extract useful information to solve the problem.
Inference	Students propose, evaluate, and select multiple adequate hypotheses that lead to the solution of the problem.	Students propose and select multiple adequate hypotheses that lead to the solution of the problem.	Students propose hypotheses that lead to the solution of the problem.	Students propose hypotheses that do not lead to the solution of the problem.
Explanation	Students justify their results using adequate equations that sustain their solution and explain their answer according to their hypothesis.	Students justify their results using adequate equations that sustain their solution and explain their answer under a general context.	Students only justify their results using adequate equations that sustain their solution.	Students do not justify their results or use good equations, nor can they explain their answers.
Questioning and reviewing	Students find more than two results using various probable hypotheses. They explore alternatives explaining the reasoning behind each answer.	Students find at least one probable hypothesis and solution explaining the reasoning behind each answer.	Students find at least one different hypothesis and solution, only explaining the reasoning of their main answer.	It is not possible for students to come up with an alternative hypothesis or solution.

Adapted to Facione (1994) and Alsaleh (2020) Creation date: **November 21, 2021, 11:00 h**