International Journal of Education, Vocational and Social Science
https://e-journal.citakonsultindo.or.id/index.php/IJEVSS
E-ISSN : 2963 4954
IJEVSS

Learning Design of Project-Based Critical Thinking in Intermediate Linear Algebra for Higher Education Students

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Abstract

This research uses a design-based approach aimed at exploring the critical thinking skills of university students through an advanced linear algebra project. The subjects involved are 32 students enrolled in the Advanced Linear Algebra course during the odd semester of the 2023/2024 academic year. To support the research, the instruments used include a critical thinking skills instrument, Hypothetical Learning Trajectory, Local Instruction Theory, Learning Activity Observation Based on Video, and a Google Drive-Based Portfolio. The data analysis technique involves several stages, starting with data condensation (transcription, coding, categorization, and theme identification), data presentation (process analysis, matrix, iterative processes, and conclusion drawing and verification), and data validity checking (triangulation and generalizability of research results). Based on the research findings, students' critical thinking skills are determined by reviewing five components: interpretation, analysis, evaluation, argumentation, and self-regulation. The harmonization and synchronization across various activities are still in the moderately developed category, indicating the need for dynamic and interactive activities to support proficiency fulfillment.

Keywords: Learning Design, Project-Based Critical Thinking, Intermediate Linear Algebra

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INTRODUCTION

The challenge faced by students today is to equip themselves with adequate competencies, one of which is critical thinking skills. (Terblanche, 2021; Treffinger, 2007). Critical thinking is a fundamental skill that enables students to tackle complex problems and think deeply about various solutions, especially in mathematics. (Perez & Andrade, 2023; Siregar et al., 2024). For higher education students, especially those studying linear algebra, developing critical thinking skills is essential for a deeper understanding of abstract concepts and their applications in the real world. In other words, students not only need to grasp the abstract concepts presented during lectures, but they are also encouraged to use that knowledge to build their own understanding and learning experiences.

The learning habits acquired by students before entering the world of higher education are generally still dominated by traditional approaches (Alghadari et al., 2022; Kolb & Kolb, 2022), especially in understanding mathematical concepts. This results in their ability to study mathematics tending to be mechanistic, relying solely on mathematical processes that depend on a combination of symbols and mathematical rules applied to solve problems (Çelik, 2018; Pitta-Pantazi et al., 2024). Such an approach limits students to solving problems without truly understanding the fundamental concepts underlying those solutions. In fact, the real goal is for students to be able to build mathematical knowledge more deeply and sustainably, enabling them to develop critical and analytical thinking skills (Al Marri & Obaid, 2023; Coates et al., 2005). The ideal learning process should encourage students to actively connect mathematical concepts with real-life situations and build a more holistic understanding (Bachtiar, 2022; Grabinger et al., 1997; Oliveira et al., 2021). Thus, students not only master problem-solving techniques but also possess innovative abilities in applying mathematics in various contexts.

To achieve this goal, a change in the approach to mathematics education in higher education is necessary. A more interactive and participatory learning method should be implemented to address the weaknesses of traditional approaches. One way to do this is by implementing problem-based learning or project-based learning (Nasrullah, 2014; Suryandari et al., 2018), which can encourage students to think more creatively and analytically. Students are encouraged not only to solve problems but also to identify relevant issues, formulate questions, and seek solutions from various perspectives. In addition, the use of technology and digital tools, such as computer simulations and mathematical software, can also help students understand abstract concepts more clearly. (Pimentel et al., 2022; Riconscente, 2013). Thus, students will have a more comprehensive ability to face academic and professional challenges in the future, as well

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as being prepared to apply their knowledge in the workforce.

One of the courses taught to students is basic linear algebra, where the material provided is not only oriented towards mathematical theory or concepts but also includes case studies that are expected to train cognitive abilities and problem-solving skills in addressing the given issues. Through this approach, students are encouraged not only to understand the basic principles of linear algebra but also to apply them in real-world contexts. (Nasrullah, 2015; Van den Heuvel-Panhuizen & Drijvers, 2014). For example, they may encounter problems related to systems of linear equations or linear transformations that often arise in various fields, such as engineering, economics, and computer science. (Margianti, 2001; Yanita & Bakar, 2021). Thus, students can develop the analytical skills necessary to face challenges in the professional world.

The classroom activities conducted by selecting the material of Elementary Linear Algebra guide students to foster collaboration in the learning process. They collaborated on completing a project to enhance critical and analytical thinking skills. (Widyastuti & Hamidah, 2017). Students are encouraged to exchange ideas, solve problems together, and consider different perspectives. This not only enriches their understanding of the material but also prepares them to face workplace situations that often require teamwork and cross-disciplinary collaboration. Thus, students can develop interpersonal skills as well as the ability to solve problems collectively and effectively. (Mcgaghie et al., 2014; Rahman, 2022).

The trajectory of this activity is designed through a systematically structured learning design, combining theoretical elements with practical applications. Project-Based Learning is implemented to allow students to explore linear algebra concepts in depth while working on problems relevant to real life (Izquierdo et al., 2016; Prescott et al., 2020). Each project is designed to challenge students to apply the theories they have learned, so they do not just memorize formulas, but also understand how these concepts can be applied in different situations. By involving students in an active and collaborative process (Weiss et al., 2019), this learning design aims to create a learning environment that supports the development of critical thinking, analytical skills, and essential teamwork abilities in the professional world.

So far, the academic activities have been focused solely on fulfilling competencies that lead to cognitive abilities, where the activities are still demonstrated through theoretical studies and problem-solving with pen and paper. Although these activities are not sufficient to support students in developing the critical thinking skills needed as a complement to the expected competencies. (Abdulah & Winarti, 2022; Brashear et al., 1995). To that end, students need the development of activities where critical thinking skills have the opportunity to be applied, and

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they use them for the development of knowledge and learning experiences.

Based on the review, this article reveals how project-based learning designed with critical thinking in mind allows students involved in the learning activities to demonstrate their critical thinking skills through the topic of linear algebra. In addition, the changes that occur in each learning process are revealed as a part that demonstrates the effects of the designed learning process. Therefore, this paper presents the study title: Learning Design of Project-Based Critical Thinking in Intermediate Linear Algebra for Higher Education Students.

METHOD

This research uses a design-based research method, which is a systematic and flexible research approach. Processes such as analysis, design, development, and implementation are carried out iteratively with the aim of developing educational practices, design principles, and theories in real-world environments in collaboration between researchers and participants. Wang & Hannafin, 2005). Design-based research differs from other design methods because the phases of design, analysis, and redesign occur in a continuous cycle (Herrington et al., 2007; Kuzu et al., 2011), and it involves the active roles of researchers and participants from the beginning to the end. In addition, design-based research reports all adjustments and changes made during the research process in detail. (Reeves, 2000). In this study, a design-based research method was applied in three cycles to determine the design principles of the learning environment.

In this study, the design - implementation - development and evaluation phases were carried out in three cycles, and the changes made in each cycle were reported in detail. Thus, by reviewing the data obtained from each cycle, adjustments were made to achieve a more successful cycle, and efforts were made to create a more efficient design. In Figure 1, the steps of the application in design-based research are shown in the form of a flowchart.

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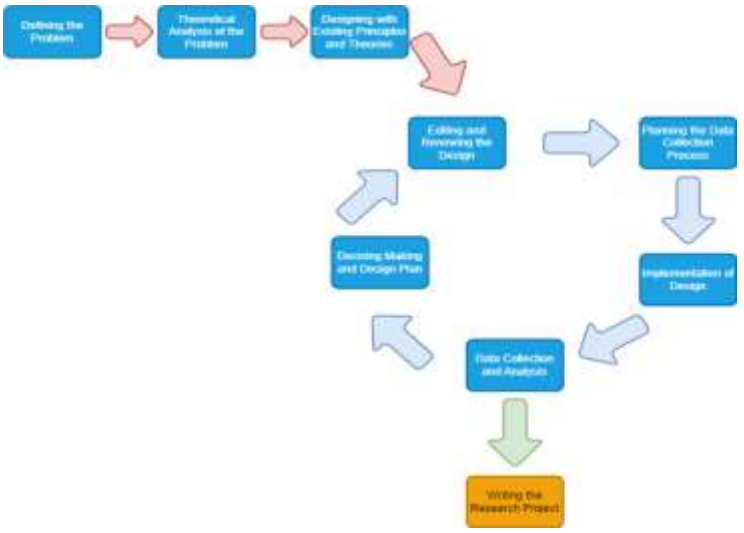


Figure 1. Research Design Flowchart

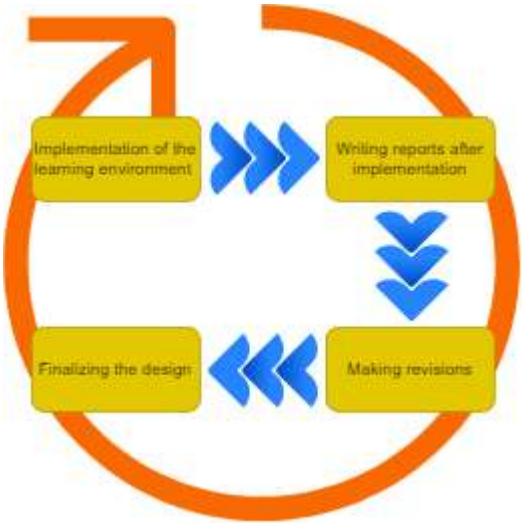


Figure 2. Implementation of the Learning Environment

Figure 2 shows how the research was conducted over one week and the procedure lasted for six weeks. As seen in figure 2, the reflection report was created immediately after the implementation of the learning where the learning environment was applied, and then revisions were made based on the data obtained from this report, video recordings, and field notes. The revision includes the removal of unnecessary questions in the worksheet, improvement of instructions, making questions easier to understand, developing the Spreadsheet template to better suit practical and theoretical backgrounds, as well as organizing the classroom

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presentation. After the revisions were made, the researchers, along with expert educators in the field, evaluated the revisions and finalized the design for the next cycle. The same process is used for each subject over 6 weeks, and the design principles are established after two cycles, allowing the research to proceed to the third cycle. The list of topics discussed during the 6-week course is presented in the table below.

Table 1. List of Topics for Linear Algebra Courses

Week	Topic
1	Real Vector Spaces
2	Subspaces
3	Linear Independence
4	Coordinates and Basis
5	Dimension
6	Change of Basis

Through the topics above, project-based learning is developed by integrating critical thinking activities where the five intended components begin with interpretation, analysis, evaluation, argumentation, and self-regulation. This ability is measured using indicators such as the table below.

Table 2. Categorization of Critical Thinking Skills Development

No	Not yet developed.	Starting to Develop	Developing as Hoped	Developing Well	Special
1	Has not yet met the basic competencies for the given topic, where the conceptual knowledge used and the procedural knowledge	It appears that there is a basic ability regarding the given topic, where the conceptual knowledge used and the procedural	It shows the basic ability for the given topic where the conceptual knowledge used and the procedural knowledge	Meeting the basic competencies for the given topic where the conceptual knowledge used and the procedural knowledge applied in solving	Meeting the flexibility of basic skills for the topic marked by comparison, self-explanation, and exploration

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No	Not yet developed.	Starting to Develop	Developing as Hoped	Developing Well	Special
	applied do not align with (solving) the given problem.	knowledge applied merely lead to the process of solving the presented problem.	applied lead to the process of solving the given problem.	the provided problems.	before instruction in solving the given problems.
2	Has not yet met the basic competencies developed for the given topic, where the conceptual knowledge used and the procedural knowledge applied are not in accordance with (solving) the given problem.	The basic skills developed for the given topic are evident, although the conceptual knowledge used and the procedural knowledge applied merely lead to the resolution of the given problem.	The basic skills developed for the given topic are evident, although the conceptual knowledge used and the procedural knowledge applied lead to the resolution of the given problem.	Demonstrating the basic flexibility of skills for the topic marked by comparison, self-explanation, and exploration before instruction in solving the given problems.	Developing the flexibility of basic skills for the topic marked by comparison, self-explanation, and exploration before instruction in solving the given problems.

To support the documentation of projects undertaken by students, all their work is stored on a Google Drive that has been organized in such a way as to facilitate not only access but also the uploading of assigned project tasks.

The number of students involved in this research is 30, all of whom are participants in the course. To support the acquisition of research data, the instruments used include video recordings and field notes. Field notes are used as the primary recording tool in qualitative research. This note is a place filled with information about people, events, activities, and conversations. In this

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note, there are observations regarding thoughts, intuitions, and emerging patterns, as well as our ability to observe the researchers' investigations and individual reactions (Glesne, 2012; Yıldırım & Şimşek, 2005). Field notes were taken during observations in the classroom environment by the researcher and the lecturer. In the field notes, observational data and comments about the process were included by the researcher and the lecturer. Both the issues that arise in the designed learning environment, the difficulties experienced by students, and the parts that students do not understand during the process are reported with field notes. Thus, it is hoped that the design can be improved by making the necessary changes and adjustments with the help of field notes after each cycle. In addition, video recordings are also made during each class.

In the scope of the research, the observational data obtained with the help of field notes kept by the lecturers and researchers is carefully reviewed after each implementation, transcribed, and transformed into a report. With the help of a detailed report, it is hoped that the design can be organized in each cycle and changes can be made if necessary. The video recordings are watched after implementation and at other times when needed, so the process can be followed and used in the analysis of field notes. The analysis is conducted based on the theoretical framework of the research to meet the pedagogical principles in teaching linear algebra, paying attention to the use of representational language, and contributing to the development of modes of thinking. In this way, the stories from the implementations carried out at the end of each cycle are created, and the revisions to be made for the next cycle are aimed to be presented publicly based on those stories. Technically, the data analysis technique involves several stages, starting with data condensation (transcription, coding, and categorization), data presentation (process analysis, matrix, iterative processes, and conclusion drawing and verification), and data validity checking. (triangulation and generalizability of research results).

RESULTS AND DISCUSSION

The implementation of project-based learning focused on critical thinking begins with the delivery of instructions by the lecturer, where the course material that serves as the foundation is presented as an introduction before students engage further in the designed learning activities. The material provided can be obtained through the e-book that is distributed to each student. The introduction to the learning activities is shown as in figure 3 documentation below.

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Figure 3. Delivery of Lecture Instructions at the Beginning of the Class

During the preliminary activity, lecture materials are presented to students as an introduction to connect the knowledge they have with the material to be given. In this process, there are field records obtained as follows.

> "Preliminary activities do play a role as an introduction to what students will obtain and use for a sustainable process in classroom activities. For this reason, students are required to gain initial knowledge at this meeting and it is hoped that they will be able to frame other sustainable activities after the meeting, such as the use of spreadsheets."

The instructions provided along with the course material are expected not only to be absorbed by the students but also to be developed, especially when addressing cases presented by the lecturer. When the material deemed suitable for the lecture is adequately delivered in that session, the students' knowledge needs to be challenged with cases to assess the extent of their achievements in presentation, as illustrated in the following figure 4.



Figure 4. Students' Writing in The Glassboard

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There is no mistake in the challenge given to students in the brainstorming session through cases presented on the glass board. A strong desire is illustrated by the writing shown on the glass board. This is also a good marker in the learning trajectory so that students can achieve the expected learning goals. With activities like this, field records that can be recorded are as follows.

> "In this activity every student wants to advance their thinking skills, especially critical thinking. However, they still seem to be hesitant and confused to what extent it can be shown in lecture activities. Sometimes the case given is too simple for the current ability. In other words, they need more complex problems to make them unyielding in their efforts."

Figure 4. Students are given the opportunity to develop their ideas through the problems presented. To solve the given case, the students demonstrated serious activity to complete it and obtain the expected solution. This seriousness is demonstrated through interactions and discussions with one another, as shown in the following figure 5.



Figure 5. Students establish interactive relationships through the given problems and discuss to find the expected solutions.

When students are aware that every lecture activity that takes place for each meeting is for them. Then equipped with the problem claims in the given task is their responsibility as well. The turning point of this process is the effort and ability to strive to grow as they become aware of meeting each of these challenges. For this reason, important things recorded in activities such as figure 5 provide the following information.

> " What is desired from the lecture activities carried out is to make them know what is given. Not only that, but they are required to achieve learning goals. However, not only

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that, the higher expectation is that they form the skills they should have acquired as a marker that they have achieved proficiency. One of those skills is the ability to think critically."

Based on the review that can be revealed from images 3, 4, and 5, the classroom activities are conducted with the aim of conditioning the learning process that can be followed by students. In this conditioning, it is hoped that their understanding of the material can be applied when solving the given problems. Certainly, the interpretative skills developed can be continued into the analysis stage, allowing them to connect the provided material with the presented problems in a clear analysis that leads to the expected problem-solving. To what extent students' analytical skills can develop during lectures is also observed periodically. Observe the image of how students construct their answers.



Figure 6. Students constructing answers based on the given problem.

Indirectly, what constitutes the artifacts of student learning outcomes in lecture meetings are interpretation skills and analytical skills. These two skills frame students' critical thinking skills to answer the cases given in each learning activity meeting. The interesting thing about giving this case is that it gives the following notes.

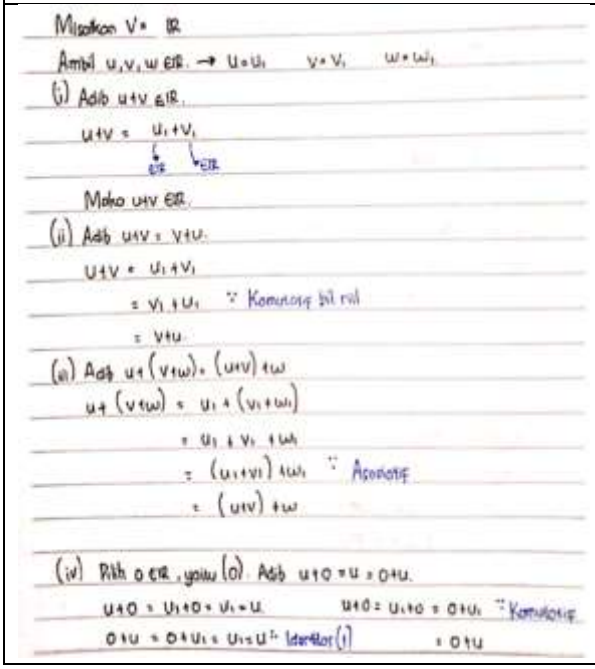
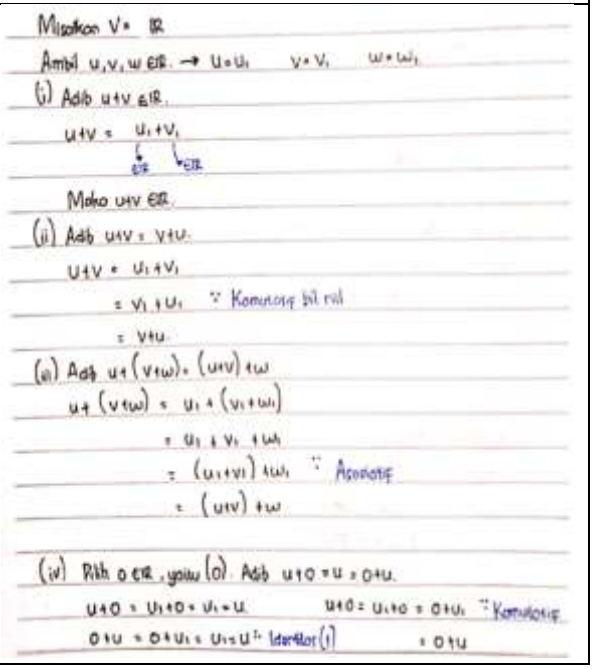
"Every assignment given to students actually does not only fulfill their cognitive abilities. Students are given the opportunity to build knowledge and learning experience. How much they write at least arouses their curiosity to form the knowledge and learning experience. Especially if they ask because this opens up a space for interpretation and analysis so that it triggers interpretation skills and analytical skills to develop."

After the students write their answers and submit the answer sheets as a learning artifact. This is done for each meeting so that every student has a collection of answers based on the topics

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discussed in each of those meetings. The answer provides an overview of what the development of knowledge and learning experiences can be demonstrated, as well as serving as material to ensure whether they can learn from each lecture session they have attended. For this reason, assessing students' abilities is part of the process to ensure that they evaluate each learning session, so the point they are at now is the result of the learning evaluations that have been conducted. Similarly, the arguments constructed in each assigned task indicate that students have undergone a transformation in every piece of knowledge and learning experience they have gained.

Original Student's Response	Translated Student's Response
	

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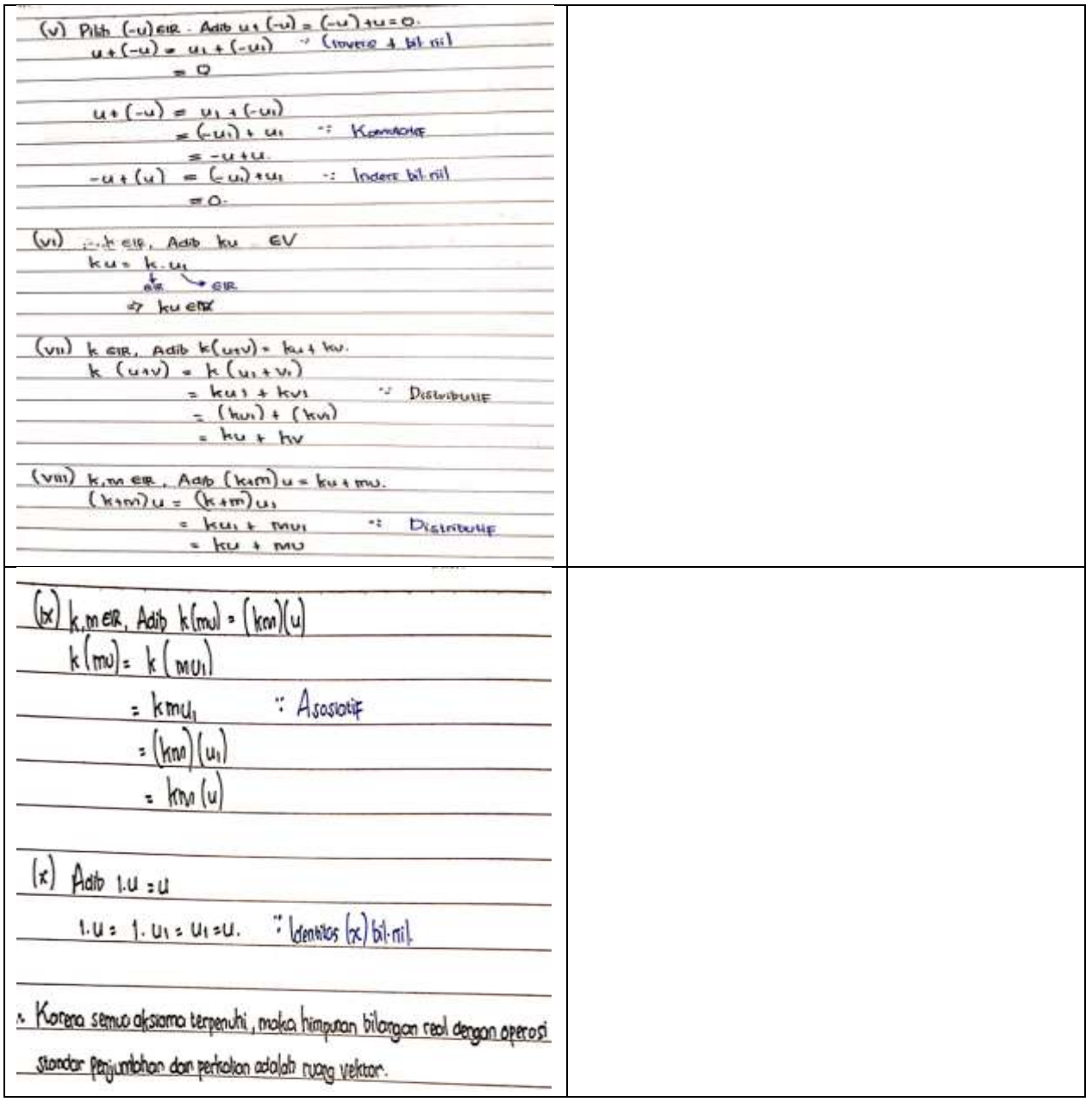


Figure 7. Example of Student Work on the Topic of Linear Algebra

Figure 7 shows the work of students in demonstrating the axioms of vector space over real numbers. If we look at what the student has done, the factual knowledge demonstrated shows the expected achievements. However, from the overall process of the lectures attended by the

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students, the progress of their learning outcomes that can be recorded is shown in the table as follows.

Table 3. Progress of Students' Critical Thinking Skills in Linear Algebra Courses

		Topic					
		Real Vector Spaces	Subspaces	Linear Independence	Coordinates and Basis	Dimension	Change of Basis
Categories of Critical Thinking Skill	Not yet developed	0	1	1	1	1	1
	Starting to Develop	0	0	0	0	0	9
	Developing as Hoped	6	10	9	7	8	6
	Developing Well	2	1	1	5	5	3
	Special	16	18	19	17	16	11
	Sum	24	30	30	30	30	30

Based on Table 3, not all students were able to demonstrate the expected learning progress. There are still students who seem to have not developed on several topics given in the class activities. It appears that only 9 individuals are still categorized as beginning to develop in the topic of change of basis. Although those in the developing category are still more numerous than those who are developing well, the learning progress obtained shows that those classified as exceptional are above half of the total for the five topics: Real Vector Spaces, Subspaces, Linear Independence, Coordinate and Basis, and Dimension. As for the topic of change of basis, 11 students successfully demonstrated exceptional ability.

From this explanation, it is indeed expected that students in the Linear Algebra course understand the transformations that occur within the topics discussed through various modes of description. (Hillel & Sierpinska, 1994). There is a smooth transition from one mode to another. Understanding and following the changes from one mode to another is one of the main reasons why students struggle to distinguish between definitions and descriptive modes. In addition to the

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descriptive mode, the reasoning mode may also be necessary to help students develop a better understanding of the differences between definitions and descriptive modes in the context of linear algebra (Açıkyıldız & Kösa, 2021). This transition requires a consistent understanding of definitions and modes of description, although this is not easy for all students. The consistency referred to here can involve the rapid introduction of abstract concepts without a strong intuitive foundation, or the use of the principle of concretization based on the idea that students can build their understanding of a particular concept in a context that is concrete for them (Harel, 2000). This is then complemented by the principle of necessity, which emphasizes the active participation of students in linear algebra lessons (Aydın, 2007), as well as the principle of generalization, which relates to didactic decisions regarding the selection of teaching materials rather than the learning process. (Harel, 2000).

To achieve consistency based on concretization, needs, and generalization, students need to develop critical thinking skills in algebra learning. (Catarino & Vasco, 2021; Izquierdo et al., 2016). These skills are aimed at independence, generating and interpreting patterns, understanding logical relationships between ideas, communicating clearly about similarities and differences, and using problem-solving skills to find the best solutions, which are identified as essential skills for students to master algebra. (Nasrullah, 2015; Sari et al., 2022). The learning trajectory is prepared where activities ignite the abilities possessed by students to demonstrate their interpretive skills through the cases or problems presented. (Moanoang et al., 2021; Nasrullah & Zulkardi, 2011). After that, students were given the opportunity to develop their analytical skills, both individually and with friends, through interactive discussions using the provided worksheets. The learning process is expected to continue, where students are guided to evaluate what they have done, what they have gained, and what skills have been developed through that process. In terms of what they have worked on, students can demonstrate a variety of arguments that are constructed either in a structured manner or even incidentally based on the challenges they have faced. Meanwhile, what they have gained and the skills developed through this process are expected to become part of self-regulation, where they can make various adjustments to the learning process they are engaged in.

CONCLUSION

Based on the results of the learning design that implements a project-based critical thinking approach for the linear algebra course, it shows that students are directed to develop their critical thinking skills, which are determined by reviewing five components: interpretation,

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analysis, evaluation, argumentation, and self-regulation. This activity is carried out through the harmonization and synchronization across various activities, which are still in the moderately developed category, indicating the need for dynamic and interactive activities to support proficiency fulfillment. Various activities begin with a conceptual transfer as a trigger to start the learning process, followed by a conceptual application through problem-solving activities that can be done individually or through discussions with involved peers. With the dynamic development of issues where not only concepts are developed, but also complex challenges presented, it will guide students to think and work with complex ideas as well.

The complexity is integrated through project-based activities carried out collaboratively by the students. For this reason, participation in working on analysis, evaluation, presenting arguments, and self-regulation becomes a key component that complements each student's abilities in that lecture forum.

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