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DESIGN AND EVALUATION OF A DEEP LEARNING-BASED ADAPTIVE CHATBOT SYSTEM FOR LEARNING ADVANCED LINEAR ALGEBRA CONCEPTS IN SUPPORT OF SUSTAINABLE DEVELOPMENT GOALS (SDGS)

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Abstract

This study presents the design and evaluation of a deep learning-based adaptive chatbot system developed to support conceptual understanding of advanced Linear Algebra concepts in higher education, contributing to the Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education). The proposed system integrates a transformer-based natural language processing model with contextual embeddings, an explainable step-by-step reasoning module, and a misconception detection mechanism to deliver adaptive mathematical feedback. A Research and Development approach employing an explanatory sequential mixed-methods design was adopted. Quantitative evaluation involved experimental testing with 30 undergraduate Linear Algebra students, while qualitative analysis examined interaction logs and interviews to explain learning mechanisms. The results show that the adaptive chatbot system significantly improves students' conceptual understanding, especially at the relational-schematic and formal-axiomatic levels, compared to conventional instruction. Qualitative findings indicate that adaptive explanations, visual representations, and error-diagnosis feature effectively support deeper mathematical reasoning and proof construction. These results demonstrate that deep learning-based chatbot systems can function as intelligent and scalable learning technologies, supporting inclusive and technology-enabled advanced mathematics education aligned with sustainable development objectives.

Keywords: Deep learning, Math chatbot, Concept understanding, Advanced mathematics, Adaptive learning.

1. Introduction

Conceptual understanding is a critical foundation in advanced mathematics learning, particularly in courses such as Linear Algebra, where students are required to interpret abstract definitions, connect symbolic representations, and construct formal mathematical arguments. At the university level, many students continue to rely on procedural manipulation without fully understanding underlying mathematical structures, leading to misconceptions and superficial learning [1, 2]. These challenges indicate the need for learning systems that support deeper conceptual and structural understanding.

Recent advances in deep learning and artificial intelligence (AI) have enabled the development of intelligent learning systems capable of adaptive interaction and explanation [3-7], especially in natural language processing (NLP). Transformer-based models demonstrate strong capabilities in processing mathematical language, generating contextual responses, and providing personalized feedback [8, 9]. In educational settings, AI-driven chatbots have emerged as intelligent tutoring systems that support problem-solving, misconception diagnosis, and concept explanation through interactive dialogue [10-12].

From a theoretical perspective, three worlds of mathematics framework describe the progression from procedural understanding to relational-schematic and formal-axiomatic reasoning. Deep learning-based chatbots can function as digital cognitive scaffolding systems by linking symbolic, visual, and conceptual representations through adaptive explanations [13]. Such systems align with the Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education), by supporting inclusive, technology-enabled, and scalable learning in higher education. This study supports current issues in SDGs as reported elsewhere [14-19].

Despite growing interest in AI for education, empirical studies on deep learning-based chatbot systems for advanced mathematics learning remain limited, especially in the Indonesian context. Therefore, this study aims to design and evaluate a deep learning-based adaptive chatbot system for Linear Algebra learning. The novelty of this research lies in (i) integrating transformer-based NLP with explainable mathematical reasoning, (ii) mapping students' conceptual understanding across procedural, relational-schematic, and formal-axiomatic levels, and (iii) positioning the chatbot as an intelligent learning system that supports sustainable, SDG-oriented advanced mathematics education.

2. Methodology

This study employed an explanatory sequential mixed-methods design to evaluate a deep learning-based adaptive chatbot system for advanced Linear Algebra learning. The study consisted of two main phases: system development and system evaluation. In the development phase, an adaptive chatbot system was designed and implemented using a transformer-based NLP model with contextual embeddings, an explainable step-by-step reasoning module, and a misconception detection mechanism.

The chatbot was developed to support core Linear Algebra topics, including vector spaces, linear transformations, eigenvalues, and eigenvectors, and was structured according to three levels of mathematical understanding: procedural, relational-schematic, and formal-axiomatic. The system integrates symbolic,

visual, and conceptual representations through adaptive dialogue and mathematical visualization modules.

In the evaluation phase, 30 undergraduate students enrolled in a Linear Algebra course participated in the study. Quantitative data were collected using a validated conceptual understanding test administered before and after the intervention and analyzed using paired t-tests and N-Gain calculations. Qualitative data were obtained from chatbot interaction logs and semi-structured interviews to explain learning mechanisms and system behavior. Data triangulation was applied to ensure the validity and reliability of the findings.

3. Results and Discussion

The implementation of a deep learning-based adaptive chatbot system significantly improves students' conceptual understanding of advanced Linear Algebra. Quantitative outcomes show that post-intervention learning gains were dominated by higher-order understanding levels. A total of 42% of students reached the formal-axiomatic level, followed by 38% at the relational-schematic level, while only 20% remained at the procedural level. These findings indicate a clear shift from procedural manipulation toward deeper conceptual and structural understanding. Additionally, substantial reductions in misconceptions (55%) and improvements in theorem-proving skills (47%) and conceptual connectivity (61%) further confirm the effectiveness of the proposed system.

The distribution of learning gains is illustrated in Fig. 1. Improvements were concentrated on the relational and formal levels of understanding. The adaptive chatbot supported higher-order cognitive development rather than reinforcing routine computational procedures, consistent with the three worlds of mathematics framework.

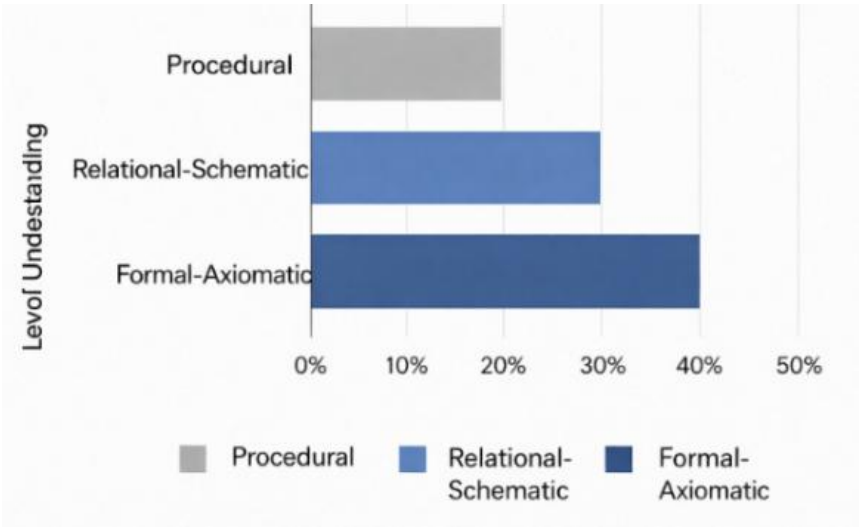

Fig. 1. Conceptual understanding improvement.

Qualitative findings summarized in Table 1 provide insight into how specific chatbot features supported learning processes. Analysis of student interactions indicates that the chatbot played a key role in visualizing abstract concepts,

providing intuitive analogies prior to formal proof construction, detecting logical errors in reasoning, and guiding students toward more coherent proof structures [10-12]. Students described the chatbot as functioning similarly to a personal tutor, particularly due to its step-by-step explanations, accurate identification of incorrect reasoning steps, and presentation of intuitive examples that facilitated understanding of formal definitions [13, 20].

Table 1. Key qualitative findings from student-chatbot interactions.

Qualitative Aspect	Description
Visualization of abstract concepts	The chatbot provides dynamic visual representations to support understanding of abstract Linear Algebra concepts.
Intuitive analogies before formal proofs	Conceptual explanations and analogies are presented prior to symbolic and formal proof construction.
Logical error detection	The system detects incorrect reasoning steps and provides corrective feedback.
Structured proof guidance	The chatbot assists students in organizing mathematical arguments and proof structures coherently.
Student perceptions	Students reported that step-by-step explanations, accurate error diagnosis, and intuitive examples supported deeper understanding of formal definitions.

These results confirm that deep learning-based chatbots are effective in improving conceptual understanding, strengthening mathematical reasoning, and supporting proof construction. The findings align with previous research on cognitive scaffolding across the three worlds of mathematics while extending its application to advanced mathematics learning supported by artificial intelligence [8, 10].

From a representational perspective, the results highlight that effective learning of advanced mathematics depends on the clarity and integration of mathematical representations. A key contribution of the developed chatbot lies in its ability to integrate symbolic, visual, and conceptual reasoning through adaptive dialogue mechanisms. This integration supports learners in constructing meaning beyond symbolic manipulation and fosters structural understanding.

The concept of linear transformation provides a concrete illustration of this mechanism. Formally defined as a mapping $T: \mathbb{R}^n \rightarrow \mathbb{R}^n$, satisfying additivity and homogeneity, linear transformations are often difficult for students to understand when presented only symbolically. As shown in Fig. 2, the transformation of the vector $\mathrm{v} = (1,1)$by matrix$\begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix}$ results in $(2, 1)$, representing a geometric stretching along the x-axis. This visualization helps students recognize matrices as representations of geometric actions on vector spaces rather than purely numerical objects.

Importantly, these visualizations are adaptively triggered based on student queries. When students ask about conceptual meanings or exhibit misconceptions, the chatbot's explainable step-by-step solver generates layered explanations that begin with geometric intuition and progressively connect to formal algebraic reasoning. This approach supports the construction of cognitive bridges between visual and symbolic representations.

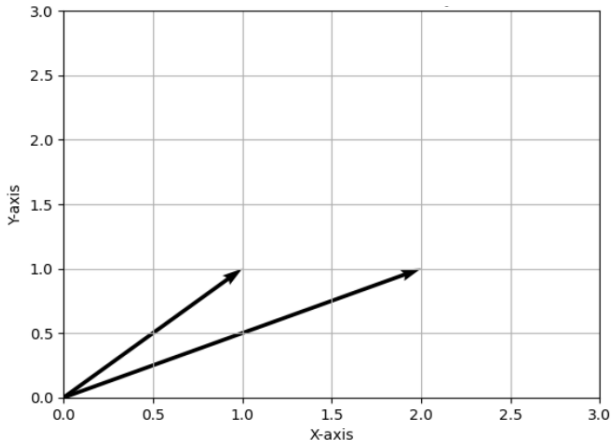

Fig. 2. Linear transformation of vector v by matrix A.

From an engineering perspective, the system integrates a transformer-based NLP model with a mathematical visualization module. Contextual embeddings identify whether a student's query concerns conceptual interpretation or numerical computation. As illustrated in Fig. 3, once the conceptual context is identified, the system retrieves relevant content from the Linear Algebra knowledge base and activates appropriate visual and narrative explanations linking algebraic and geometric representations [8, 9, 12, 21]

From a sustainability perspective, the developed chatbot system aligns with the SDGs, particularly SDG 4 (Quality Education). By providing adaptive, explainable, and scalable support for advanced mathematics learning, the system contributes to technology-enabled access to high-quality higher education and demonstrates how intelligent learning systems can support sustainable educational innovation. This adds new information in mathematics education, as reported elsewhere [22-26].

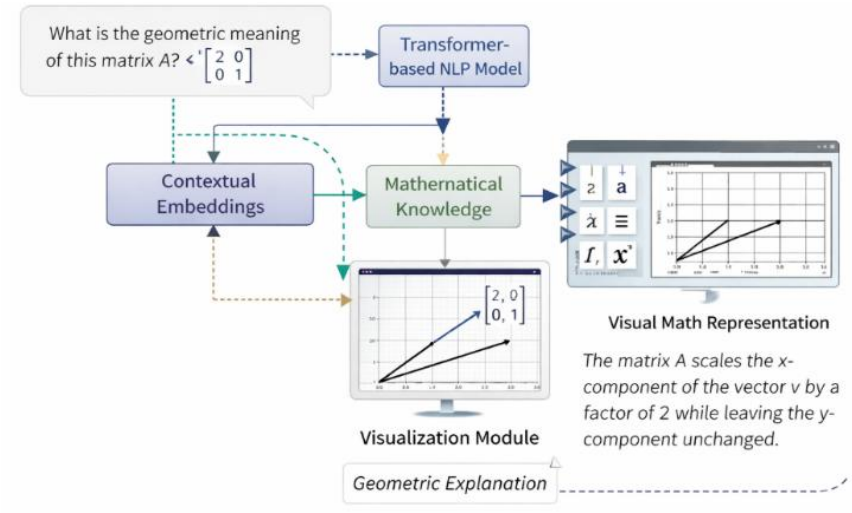

Fig. 3. Engineering perspective Chatbot.

4. Conclusion

This study demonstrates that a deep learning-based adaptive chatbot system can effectively enhance students' conceptual understanding of advanced Linear Algebra. By integrating a transformer-based NLP model, explainable step-by-step reasoning, misconception detection, and adaptive visual representations, the system supports students' progression from procedural understanding to relational and formal-axiomatic reasoning. Quantitative and qualitative findings confirm improvements in higher-order mathematical reasoning and proof construction. From an engineering perspective, the results highlight the importance of meaningful representation and adaptive system design rather than model complexity alone. Furthermore, the proposed system aligns with SDG 4 (Quality Education) by enabling scalable, technology-enhanced, and high-quality learning support for advanced mathematics in higher education.

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