Adoption of Bayesian Knowledge Tracing With Fuzzy Logic in the Development of Personalized Math Learning System for Grade 3 and 4

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Abstract

This study developed and evaluated Math Tagumpay, a Bayesian-Fuzzy hybrid Intelligent Tutoring System (ITS) designed for Grade 3–4 mathematics in the Philippines. Addressing the urgent need for innovative instructional approaches in a context where 82% of Grade 4 students fall below minimum proficiency levels, the research employed a descriptive-quantitative methodology with 10 mathematics teachers from Bataan Province. The system implements a novel sequential architecture where Bayesian Knowledge Tracing (BKT) parameters serve as inputs to a Fuzzy Logic engine to manage the partial understanding states characteristic of young learners. The evaluation revealed exceptional technical performance, with System Accuracy achieving a weighted mean of 4.30 (94% positive response) and System Timeliness reaching 4.20 (94% positive response). The Technology Acceptance Model (TAM) assessment yielded an overall weighted mean of 4.04 (85% positive response), with Attitude Toward Using (4.26) and Perceived Usefulness (4.22) emerging as primary drivers of acceptance. While Perceived Ease of Use (3.68) was identified as an area for improvement, the findings validate that sophisticated AI can be successfully adapted for resource-constrained environments through cultural sensitivity and curriculum alignment. The study concludes that the hybrid AI approach effectively addresses the complexity of elementary mathematics learning and provides a scalable framework for enhancing instructional effectiveness in the Philippine educational system.

Keywords: intelligent tutoring system, Bayesian Knowledge Tracing, fuzzy logic, Philippines, elementary mathematics

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Introduction

Traditional pedagogical approaches often struggle to meet the complex needs of modern young learners, despite decades of foundational research. This challenge is particularly acute in early childhood education, which critically shapes a child's holistic development into adulthood. While Intelligent Tutoring Systems (ITS) offer transformative potential for personalized learning and 21st-century skill development, any technological intervention must remain developmentally appropriate. Successful digital tools must balance structured activity with exploration, harnessing children's natural learning processes rather than constraining them.

In the Philippines, the need for innovation is urgent, as 82% of Grade 4 students fall below minimum mathematics proficiency levels. This creates a central tension: adapting sophisticated AI to serve resource-constrained environments while maintaining technical excellence and cultural appropriateness. While Bayesian Knowledge Tracing (BKT) has revolutionized student modeling through probabilistic tracking, it has historically focused on older learners. Conversely, fuzzy logic excels at managing partial knowledge and ambiguous responses typical of younger students. This research explores a hybrid Bayesian-Fuzzy approach, combining temporal knowledge modeling with nuanced uncertainty handling to address the unique complexities of early elementary mathematics learning.

Literature Review

The Global Educational Technology Revolution and Local Realities The transformation of education through technology represents a significant paradigm shift, with Intelligent Tutoring Systems (ITS) fundamentally reshaping how students interact with mathematical content (VanLehn, 2011). This global trend creates unprecedented opportunities for personalized learning that adapts to individual needs through continuous assessment and feedback mechanisms (Chrysafiadi & Virvou, 2013). However, these technological advances must be examined within specific sociocultural contexts. From a cultural psychology perspective, educational processes are deeply influenced by learners' cultural environments, values, and instructional traditions (Bernardo, 2017). In the Philippine context, this challenge is particularly urgent. The Department of Education (2023) reported that 82% of Grade 4 students in the Philippines fall below minimum mathematics proficiency levels. Despite these challenges, comprehensive analysis of eLearning provides evidence that technology can help students develop necessary 21st-century skills (UNESCO, 2012). Key benefits identified include increased student engagement, enhanced teacher attitudes toward innovation, and improved family interaction to support curriculum continuity (UNESCO, 2012).

Early Childhood Education and Digital Learning Evolution Integrating digital technologies into early childhood education is a considered evolution rather than a departure from developmental principles. Research has shown that appropriately designed ICT tools can enhance young learners' cognitive development when teachers remain actively involved in mediating content and learning experiences (Drigas & Kokkilia, 2015). Interactive multimedia learning environments have been shown to support foundational mathematics skills and conceptual understanding among young learners (Nusir et al., 2012). Moreover, intelligent learning systems that promote interaction and immediate feedback contribute to sustained learner engagement and meaningful knowledge construction (Liu et al., 2016). This reinforces the principle that technology should enhance, not replace, human relationships in early learning environments.

Developmental Appropriateness and Interactive Learning Effective curricula must reflect current child development research, maintaining a balance between play and structured, teacher-initiated exploration (Corpuz et al., 2016). This approach aligns with Jean Piaget's philosophy that play meets the physical, intellectual, language, emotional, and social needs (PILES) of children (Corpuz et al., 2016). Practical implementations have shown that properly designed multimedia e-storybooks enrich comprehension (Smeets & Bus, 2012), while digital storytelling serves as an expressive tool that fosters positive interactions between students and teachers (Papadimitriou et al., 2013).

Methodology

This study employs a descriptive-quantitative research design to systematically develop and evaluate the Math Tagumpay Bayesian-Fuzzy hybrid Intelligent Tutoring System (ITS). The research utilizes a descriptive method to accurately capture the characteristics and performance of the system in the context of Grade 3–4 mathematics in the Philippines. This alignment follows Dulock's (1993) definition of descriptive research, which emphasizes the systematic description of facts related to a specific area of interest.

Because the study relies on numerical representations to measure system performance—specifically accuracy and timeliness—as well as user acceptance through Likert scale assessments, a quantitative approach is most suitable. This methodology follows Babbie's (2010) framework, which prioritizes objective measurements and the statistical analysis of data gathered through structured questionnaires and polls.

The descriptive approach is particularly appropriate for this research as it focuses on the development and validation of a specialized AI tool for the Philippine educational landscape. This ensures that the ITS is evaluated within real-world educational settings, addressing the unique learning needs of Filipino students in Grades 3–4 across diverse environments. By utilizing this methodology, the study achieves a comprehensive assessment of technical performance metrics and technology acceptance indicators while maintaining scientific objectivity.

The framework for this research is further grounded in the Input-Process-Output (IPO) Model. The Inputs include the pedagogical challenges faced by teachers and the technical requirements for accuracy and timeliness. The Process involves the 2-week implementation and survey administration, and the Output is the validated Math Tagumpay system. This structured methodology provides the rigor necessary for academic publication, ensuring that both the technical architecture and the human-centered acceptance are thoroughly documented.

Software Development

The development of the Math Tagumpay system utilized the Design-Based Research (DBR) methodology, which integrates the iterative cycles of analysis, design, and evaluation to create effective educational interventions. This systematic process ensures that the resulting Intelligent Tutoring System (ITS) is not only technologically advanced but also pedagogically sound and grounded in the practical needs of the classroom.

Development Phases and Technical Implementation

The research procedure was divided into three distinct stages: analysis, design and implementation, and evaluation. During the analysis stage, interviews with Grade 3–4 mathematics teachers identified critical gaps in traditional instruction, such as the difficulty of providing personalized interventions and tracking individual progress. The design and implementation stage followed, where modern web technologies like React.js and Supabase were employed to create a cross-platform, secure environment capable of executing complex AI-driven decisions in real-time.

Sequential Processing and Algorithmic Innovation

The system architecture implements a novel sequential processing approach where the outputs of the Bayesian Knowledge Tracing (BKT) model serve as the primary inputs for the Fuzzy Logic engine. Unlike traditional parallel hybrid systems, this design enables sophisticated two-stage uncertainty refinement, allowing fuzzy logic to operate on refined knowledge parameters rather than raw student responses. This approach addresses the variable response patterns characteristic of third- and fourth-grade learners while maintaining real-time responsiveness.

To develop the Math Tagumpay system, the researchers used modern web technologies optimized for Philippine educational contexts. The frontend utilizes React.js for cross-platform compatibility and responsive design, deployed via Netlify's global CDN for fast loading in resource-constrained environments. The backend combines Netlify Functions with Supabase PostgreSQL for scalable serverless architecture.

Figure 1
System Architecture of Math Tagumpay Bayesian-Fuzzy Hybrid ITS for Grade 3–4 Mathematics

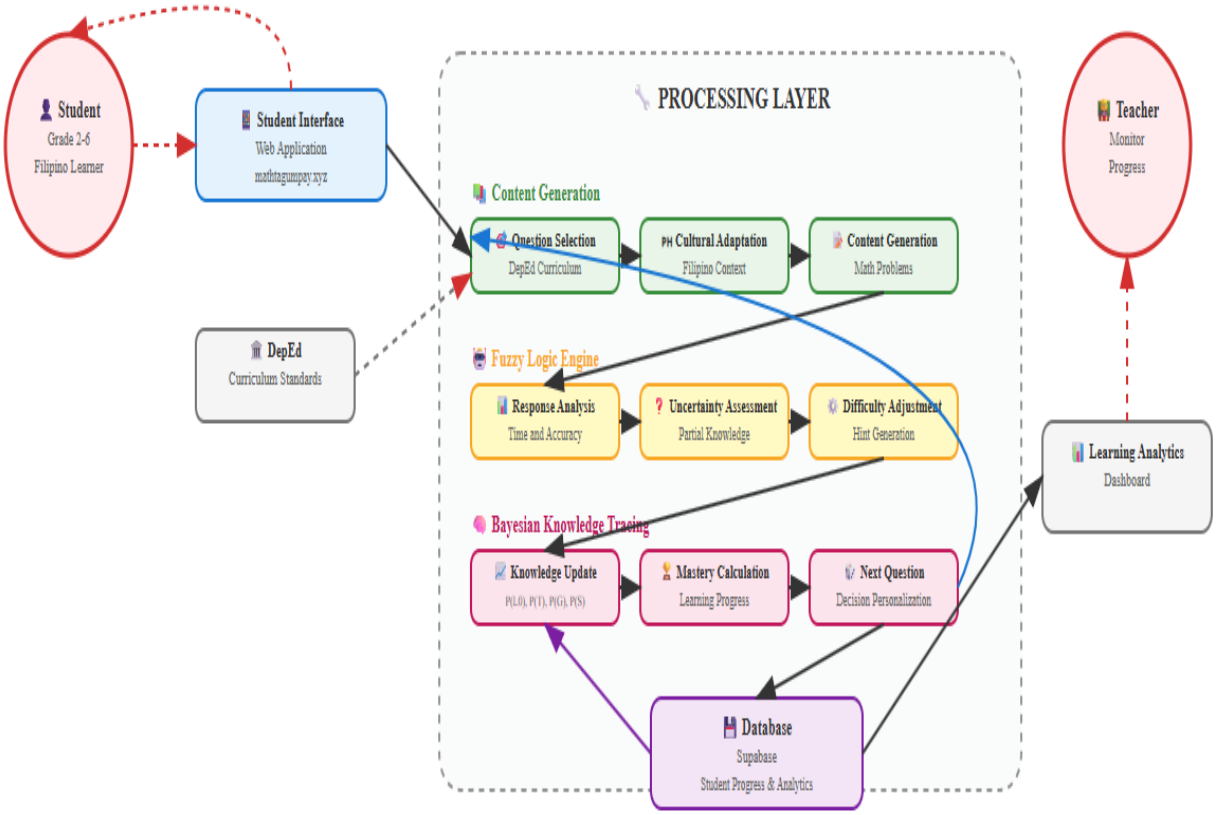

Table 1
Development Tools and Technology Stack

Category	Technology Used	Purpose
Frontend Framework	React.js	Component-based UI for age-appropriate interfaces
Backend/Database	Supabase (PostgreSQL)	Scalable data storage and real-time synchronization
Deployment	Netlify CDN	Fast loading in resource-constrained environments
AI Algorithm 1	Bayesian Knowledge Tracing	Probabilistic modeling of student learning progression
AI Algorithm 2	Fuzzy Logic Engine	Nuanced handling of uncertain student responses

Results and Discussion

The comprehensive evaluation of the Math Tagumpay Bayesian-Fuzzy hybrid Intelligent Tutoring System provides empirical evidence of its technical performance and user acceptance. The results are based on a 2-week implementation period involving 10 Grade 3–4 mathematics teachers in Bataan Province.

System Performance Assessment

The system achieved exceptional ratings across both accuracy and timeliness dimensions, with an overall performance weighted mean of 4.25 and a 94% positive response rate. The architecture successfully managed the partial understanding states characteristic of young learners while maintaining real-time responsiveness. This performance confirms that the hybrid approach is superior to single-algorithm methods for early elementary learners.

Technology Acceptance Evaluation

User acceptance was measured using the Technology Acceptance Model (TAM) framework, achieving an overall weighted mean of 4.04. Teachers demonstrated high perceived usefulness (4.22) and positive attitudes (4.26) toward the system. While behavioral intention (3.98) remained strong, the perceived ease of use (3.68) was identified as a critical area for ongoing interface optimization and teacher training.

The data analysis reveals that teachers highly value the system's ability to enhance instructional effectiveness:

The teaching effectiveness enhancement achieved the highest rating (M = 4.50) with 100% positive response rate, supporting meta-analytical findings that educational AI systems require high perceived usefulness scores for sustainable adoption. This result validates that perceived usefulness serves as the primary determinant of technology acceptance in the Philippine educational context.

Conclusion

The developed Bayesian-Fuzzy hybrid ITS demonstrates exceptional technical performance for third- and fourth-grade mathematics education in the Philippines. By successfully

integrating Bayesian Knowledge Tracing with fuzzy logic, the system achieves high accuracy in content generation and knowledge assessment while maintaining the real-time responsiveness essential for young learners. This hybrid AI approach effectively addresses the complexity of early elementary learning by managing the partial understanding states and variable response patterns characteristic of students in this age group.

The system achieved strong user acceptance among Filipino mathematics teachers, who demonstrated high perceived usefulness and positive attitudes toward its implementation. These findings validate the viability of advanced AI technologies in resource-constrained educational environments, showing that sophisticated systems can enhance instruction when properly designed and culturally adapted. However, moderate ease-of-use scores indicate that user experience optimization remains a primary area for enhancement, requiring improved interface design and comprehensive training programs to maximize long-term effectiveness.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The author declares that Gemini, an AI-assisted technology, was used in the refinement and formatting of this manuscript. The usage was limited to condensing existing content for clarity, applying specific markdown formatting styles, and ensuring consistent citation structures. The author further declares that the core ideas, research design, methodology, findings, and analysis are originally derived from the systematic conduct of the research.

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