

Development of a Pirie-Kieren Based Quadratic Equation Module Integrated with Game-Based Learning

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ABSTRACT

Mathematics learning requires instructional materials that not only present concepts systematically but also facilitate students' conceptual understanding. One approach that can be employed is the Pirie–Kieren Theory, which explains the progressive development of mathematical understanding and can be integrated with game-based learning media to enhance student engagement. This study aimed to develop a teaching module on quadratic equations based on the Pirie–Kieren Theory integrated with the Bamboozle mathematics game. The study employed a Research and Development (R&D) method using the ADDIE model, consisting of the Analysis, Design, Development, Implementation, and Evaluation phases. The developed module was validated by experts and subsequently implemented with tenth-grade students at SMAN 3 Sampang. The research instruments included expert validation sheets, student response questionnaires, and a conceptual understanding test. The findings indicate that the developed teaching module is valid, practical, and effective, making it suitable for facilitating the improvement of students' conceptual understanding of quadratic equations.

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1. Introduction

Mathematics learning on quadratic equations at the senior high school level can be challenging because students may memorize procedures without understanding the underlying concepts [1]. This difficulty was identified through observations and interviews with mathematics teachers at SMAN 3 Sampang in October 2025: students could solve problems similar to worked examples but experienced difficulty when the problems were modified [2]. These observations indicate a need for learning materials that make conceptual relationships explicit and provide opportunities for students to explain, test, and revise their reasoning.

Quadratic equations are an important algebra topic introduced in junior high school and developed further in Grade 10, where the topic builds on algebraic operations and linear

equations [3]. Solving quadratic equations therefore requires more than following a sequence of procedures; students need to understand the meaning of the coefficients, roots, and equivalent forms of an equation [4]. Teacher-dominated instruction with limited interaction may reduce opportunities for students to articulate and develop this understanding [5].

The Pirie–Kieren Theory describes mathematical understanding as a dynamic, non-linear process involving eight layers: Primitive Knowing, Image Making, Image Having, Property Noticing, Formalising, Observing, Structuring, and Inventising. Learners may fold back to an earlier layer when they encounter a difficulty, using earlier knowledge to refine their understanding [6,7]. In this study, the theory is used not only to describe understanding but also to organize learning activities: students begin with familiar knowledge, construct and interpret representations, notice properties, formalize factoring procedures, examine relationships, structure their reasoning, and apply or extend their understanding. These are intended instructional opportunities; the present pretest–posttest design does not directly establish that every student progressed through all eight layers.

Game-based learning can create opportunities for active participation and feedback, and previous research on Baamboozle has reported benefits for students' engagement and learning in a different mathematical topic [8]. The platform uses question prompts and game elements such as points and team competition; its contribution depends on how the teacher aligns the questions with learning objectives and follows up students' answers. Accordingly, Baamboozle is used here as a delivery and practice medium, while the Pirie–Kieren framework guides the conceptual sequence of the module. The game itself is not treated as evidence that conceptual understanding has improved.

Prior studies provide two relevant strands of evidence. Research applying the Pirie–Kieren framework has primarily analyzed how students' mathematical understanding develops [6,7,10,11,17,18], while research on game-supported mathematics learning has examined engagement or learning outcomes in particular contexts [8,16]. These strands suggest a rationale for combining a theory of conceptual growth with a game-based learning medium, but they do not by themselves establish the effectiveness of this particular combination. The contribution of the present study is the design and preliminary evaluation of a quadratic-equation module that uses the Pirie–Kieren layers to organize activities and Baamboozle to support question-based practice. This contribution is specific to the module developed and the limited trial reported here; it should not be interpreted as proof that no related study exists.

The module links the eight Pirie–Kieren layers to a sequence of learning opportunities and uses Baamboozle questions for guided practice. For example, introductory questions activate prior knowledge; prompts and examples support image construction and recognition; comparison tasks invite students to notice properties; and factoring questions support formalization and application. The later layers—Observing, Structuring, and Inventising—should be represented in the module through tasks that ask students to examine relationships, organize general reasoning, and extend or apply ideas. Because the study did not collect layer-by-layer process data, the alignment described here concerns the instructional design rather than a measured trajectory of individual students' understanding [11].

This study aims to: (1) develop a quadratic-equation teaching module integrating the Pirie–Kieren Theory with the Baamboozle mathematics game; and (2) evaluate the module's validity, practicality, and preliminary learning outcomes among Grade 10 students at SMAN 3 Sampang. The study used a one-class implementation; therefore, the findings are limited to this trial context and are not intended to establish causal effectiveness or generalizability beyond the participating class.

2. Methods

This study used a research-and-development (R&D) approach with the ADDIE model: Analysis, Design, Development, Implementation, and Evaluation [12]. The Analysis phase identified students' difficulties and curriculum needs. The Design phase specified learning objectives, activities, assessments, and the intended mapping to the Pirie–Kieren layers. During Development, the module was prepared and reviewed by one validator. Based on the validation feedback, the time allocation was adjusted and the names of the Pirie–Kieren layers were translated into Indonesian. During Implementation, the module was trialled with one class, and student responses and pretest–posttest scores were collected. During Evaluation, the validation results, questionnaire responses, and test-score changes were reviewed to assess product feasibility, practicality, and preliminary learning outcomes.

The study examined the development process and the validity, practicality, and preliminary effectiveness of a quadratic-equation teaching module based on the Pirie–Kieren Theory and the Baamboozle mathematics game for Grade 10 students at SMAN 3 Sampang.

The population comprised Grade 10 students at SMAN 3 Sampang in the 2026/2027 academic year. The trial sample consisted of 31 students in class X Merdeka 1, selected purposively because the needs analysis identified difficulties with quadratic-equation concepts. The research object was a teaching module on solving quadratic equations using factoring, developed based on the Pirie–Kieren Theory and supported by the Baamboozle mathematics game. As the trial involved one class, the results are intended for preliminary product evaluation rather than broad generalization.

To protect participants' privacy, students' names are reported using initials. The study involved students with varying levels of ability.

The research was conducted at SMA Negeri 3 Sampang, Jl. Diponegoro No. 24a, Randar Kumalas, Banyuwangi, Sampang District, Sampang Regency, East Java. This school is a state school, accredited A, and has implemented the Merdeka Curriculum. The research took place from February to June 2026.

Data were collected using three instruments: (1) an expert-validation sheet for the teaching module; (2) a student-response questionnaire to assess practicality after implementation; and (3) pretest and posttest items to examine learning outcomes. The module was reviewed by Dr. Moh. Zayyadi, M.Pd., a Mathematics Education lecturer at Universitas Madura. The thesis identifies the validator on the basis of his expertise and track record in mathematics education, particularly in designing and developing teaching modules. The thesis appendices also include a validation sheet for the pretest and posttest items. However, the thesis does not report a numerical validity coefficient for the test items or a statistical reliability coefficient; therefore, these coefficients cannot be claimed in this study.

Module feasibility was assessed by one expert validator, Dr. Moh. Zayyadi, M.Pd., a Mathematics Education lecturer at Universitas Madura. He was selected based on his expertise and track record in mathematics education, especially in teaching-module design and development. The validation sheet assessed six aspects: completeness of module components, content suitability, learning-presentation suitability, assessment suitability, learning partnership and environment, and language and layout. Ratings were converted to percentages and interpreted using the categories in Table 1 [13]. The overall module-validation score was 95.71%. This percentage indicates the expert's appraisal of the module, rather than statistical evidence of test reliability.

Table 1. Classification of Validity Assessment Aspects

Percentage (%)	Classification
90 – 100	Very Valid
80 – 89	Valid
65 – 79	Fairly Valid
55 – 64	Less Valid
≤ 55	Invalid

Practicality was assessed using students' responses after the module trial. Questionnaire results were summarized as percentages and interpreted using the categories in Table 2, following the approach attributed to Akbar [14]. The overall student-response average was 92.00%. The study records report this aggregate result; item counts, response options, and a separate reliability coefficient for the questionnaire are not reported in the thesis text available for this manuscript.

Table 2. Classification of Practicality Assessment Aspects

Presentase (%)	Classification
90 – 100	Very Practical
80 – 89	Practical
65 – 79	Fairly Practical
55 – 64	Less Practical
≤ 55	Impractical

Learning outcomes were examined using pretest and posttest scores, analyzed with a paired-samples t-test and normalized gain (N-Gain) in SPSS, with N-Gain interpreted according to Table 3 [15]. The thesis includes a pretest/posttest validation sheet in its appendices, indicating expert review of the test items. However, it does not report a numerical test-validity coefficient or a statistical reliability coefficient. Accordingly, this manuscript reports the documented expert review and outcome analysis but does not claim that statistical reliability was established. The instrument's score range, item-level scoring details, and assumption checks should be added only if they are available in the original test and analysis records.

Table 3. N-Gain Effectiveness Interpretation Categories

Percentage (%) N-Gain	Interpretation
> 76	Effective
56 – 75	Fairly Effective
40 – 55	Less Effective
< 40	Ineffective

3. Result and Discussion

3.1 Analysis Phase

A needs analysis was conducted through observations in class X at SMAN 3 Sampang in February 2026. The observation results showed that the learning process was still fairly conventional; teachers mostly delivered material on the whiteboard, while students only took notes and answered questions. Interviews with the teacher confirmed that students had difficulty with the concept of roots and the general form of quadratic equations, and tended to memorize procedures without understanding the underlying concepts.

The material analysis was based on the Deep Learning tenth-grade even-semester curriculum, which covers the general form of a quadratic equation as follows.

$$ax^2 + bx + c = 0 \quad (1)$$

Equation (1) shows the general form of a quadratic equation, where a is the coefficient of x^2 , b is the coefficient of the variable x , c is the constant, and $a \neq 0$. In addition, the material analysis also covers solving quadratic equations using the factoring method. The analysis results were then mapped onto the eight layers of the Pirie-Kieren Theory as the basis for formulating the learning objectives.

3.2 Design Phase

Based on the analysis results, the researcher developed a teaching module design that follows the Merdeka Curriculum format, comprising: module identity, identification of student needs, learning design, learning experiences based on the Pirie-Kieren layers, and learning assessment. The module was designed for two meetings, each allocated 2 lesson hours $\times$ 45 minutes.

The Bamboozle mathematics game was selected as a supporting medium because it features gamification elements such as points, a leaderboard, and instant feedback. The questions in Bamboozle were designed in alignment with the Pirie-Kieren stages, from the introduction of basic concepts to the application of factoring procedures.

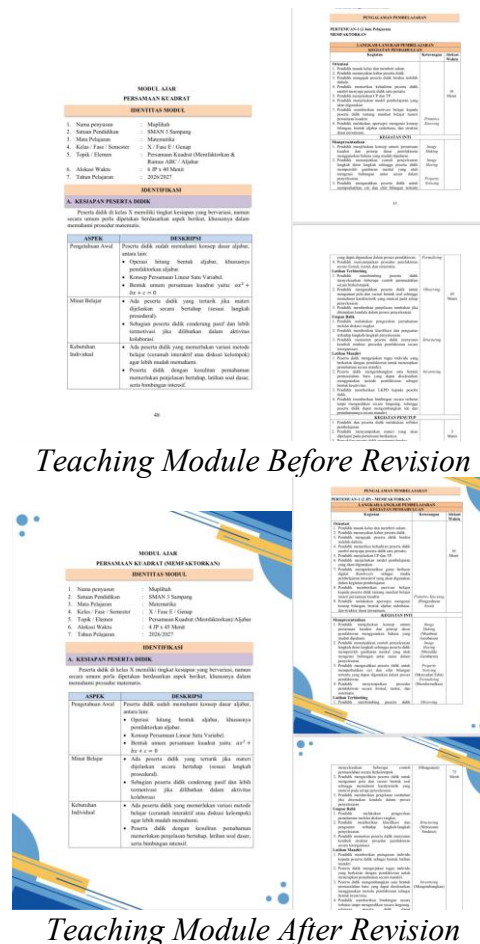
3.3 Development Phase - Expert Validation

The developed module was reviewed by one expert validator, Dr. Moh. Zayyadi, M.Pd., a Mathematics Education lecturer at Universitas Madura. According to the thesis, he was selected because of his expertise and track record in mathematics education, particularly in designing and developing teaching modules. The validation covered six aspects: module-component completeness, content suitability, learning-presentation suitability, assessment suitability, learning partnership and environment, and language/layout. The reported overall average was 95.71%. The thesis also includes a separate validation sheet for the pretest and posttest items in its appendices; however, it does not report a numerical validity coefficient or statistical reliability coefficient for those tests.

Table 4. Teaching Module Validation Results

No	Assessment Aspect	Validation Score (%)
1	Completeness of Teaching Module Components	96.88%
2	Content Feasibility	90%
3	Learning Presentation Feasibility	96.88%
4	Learning Assessment Feasibility	100%
5	Learning Partnership and Environment	100%
6	Language and Layout Feasibility	90%
Overall Average		95.71%

The module received an overall validation score of 95.71%, classified as “Very Valid” under the criteria in Table 1. The validator recommended adjusting the time allocation and translating the Pirie–Kieren layer terms into Indonesian. Both revisions were incorporated into the final module. These changes document how the module was revised following expert review. The validation score supports the expert appraisal of the product but should not be interpreted as evidence of learning effectiveness.



Teaching Module Before Revision
Teaching Module After Revision
Figure 1. Example of Product Revision

3.4 Implementation Phase - Student Response Questionnaire

A limited trial was conducted with 31 students in class X Merdeka 1 at SMAN 3 Sampang over two meetings in May 2026. On 12 May, students studied the general form of quadratic equations and factoring concepts, followed by a Baamboozle game session. On 19 May, the lesson continued with a more structured explanation of factoring; students then completed the worksheet and response questionnaire. The trial provides evidence about implementation in this class and over this short period only.

Table 5. Results of the Student Response Questionnaire Analysis

No	Aspect	Average (%)
1	Learning Media	91.50%
2	Learning Material	92.00%
3	Usefulness	92.50%

Overall Average

92.00%

The student-response questionnaire produced an overall average of 92.00%, categorized as “Very Practical” using Table 2. This result indicates that the participating students rated the module positively on the questionnaire’s measured aspects. Observations during the sessions also described active participation, particularly during the game. However, these responses are perceptions of practicality and engagement; they do not independently demonstrate conceptual learning or establish that Baamboozle caused the observed participation.



Figure 2. Documentation of Product Implementation

3.5 Module Effectiveness: Pretest and Posttest Results

The pretest and posttest scores were used to describe changes in students’ performance after the module was implemented. Figure 3 summarizes the reported results. Because this was a one-group pretest–posttest trial without a comparison group, score changes should be interpreted as improvement observed during implementation, not as proof that the module alone caused the improvement.

Bootstrap Specifications	
Sampling Method	Simple
Number of Samples	1000
Confidence Interval Level	95.0%
Confidence Interval Type	Percentile

Paired Samples Statistics							
			Statistic	Bias	Std. Error	Bootstrap ^a 95% Confidence Interval Lower	Upper
Pair 1	Pretest	Mean	16.77	.08	2.02	12.90	20.81
		N	31				
		Std. Deviation	11.44	-.200	.969	9.217	13.061
		Std. Error Mean	2.055				
	Posttest	Mean	83.35	-.01	2.22	78.26	87.06
		N	31				
		Std. Deviation	12.81	-	4.245	4.747	19.384
		Std. Error Mean	2.301	1.011			

a. Unless otherwise noted, bootstrap results are based on 1000 bootstrap samples

Paired Samples Test										
Paired Differences							t	df	Significance	
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				One-Sided p	Two-Sided p
					Lower	Upper				
Pair 1	Pretest - Posttest	-66.581	18.011	3.235	-73.187	-59.974	-20.583	30	.000	.000

Figure 3. Pretest, Posttest, and N-Gain Results

For the 31 participating students, the reported mean score increased from 16.77 on the pretest to 83.35 on the posttest. The paired-samples test was reported as $t(30) = -20.583$, $p < .001$ (the software output of 0.000 should be reported as $p < .001$), with a 95% confidence interval for the mean difference from -73.187 to -59.974 . The reported mean N-Gain was 78.9%, categorized as “Effective” according to the study’s classification. These statistics indicate a substantial pretest–posttest difference in this sample. Their interpretation depends on the test’s score range, content equivalence, scoring procedure, and the assumptions of the paired-samples test, which should be described explicitly. In the absence of a comparison group, maturation, testing effects, and other influences cannot be ruled out; the results therefore do not establish a causal effect of the module.



Figure 4. Documentation of Product Implementation

The module was designed to connect learning activities with the Pirie–Kieren framework, from activating prior knowledge and constructing or recognizing images to noticing properties and formalizing factoring procedures. The design also provides opportunities for students to observe relationships, structure reasoning, and extend their ideas. However, the data reported here consist mainly of overall test scores and student responses; they do not show which layer each student reached or whether folding back occurred. Therefore, the findings support the feasibility of organizing instruction around the framework, but a claim that the eight layers were empirically demonstrated would require process evidence such as students’ written work, recorded explanations, or systematic classroom observations.

Baamboozle provided a game format for practicing questions and may have supported participation through team competition and points. The positive student-response results and classroom observations are consistent with the possibility that the game helped sustain engagement, while prior research has reported benefits of gamification in other settings [16]. Nevertheless, this study did not isolate the contribution of Baamboozle from the module, teacher guidance, or other features of instruction. Its independent effect on learning therefore cannot be determined from the current design.

This study has several limitations. First, the implementation covered only two meetings, so retention and longer-term outcomes were not examined. Second, it involved one class without a comparison group, limiting generalizability and preventing causal attribution of score changes to the module alone. Third, access to devices and internet connectivity may affect implementation. Finally, the reported outcome data do not trace students’ reasoning through each Pirie–Kieren layer. Future studies should involve larger and more varied samples, use a suitable comparison design where feasible, assess retention over time, and collect process data such as student work, recorded explanations, and systematic classroom observations.

The findings suggest that the module can be developed and implemented in this classroom and received high expert-validation and student-response percentages. The pretest–posttest results also show a substantial score increase in the participating class. However, the study did not directly measure students’ movement through the eight Pirie–Kieren layers, and the one-group design cannot determine whether the module alone

produced the observed increase. Further evaluation should connect specific learning tasks to evidence of students' reasoning and examine the module in additional settings.

4. Conclusion

This study developed a quadratic-equation module on factoring that integrates the Pirie–Kieren Theory with the Baamboozle mathematics game for Grade 10 students at SMAN 3 Sampang. The module received an overall expert-validation score of 95.71% (“Very Valid”), and the student-response questionnaire yielded an average of 92.00% (“Very Practical”). Among the 31 students in the one-class trial, the mean score increased from 16.77 on the pretest to 83.35 on the posttest, and the reported mean N-Gain was 78.9%. These findings provide preliminary evidence that the module was considered feasible by the validator and practical by the participating students, while scores improved during implementation. Because the trial had no comparison group and did not trace students' reasoning layer by layer, the results do not establish a causal effect or confirm that every Pirie–Kieren layer was achieved.

Further research should examine the module in more classes and school settings, include a comparison condition where feasible, and assess retention over time. Researchers should also collect process data—such as students' written solutions, explanations, and classroom interactions—to investigate how understanding develops across the Pirie–Kieren layers and when folding back occurs. Future reports should describe the validator's qualifications and selection criteria and provide documented details of the instruments, scoring procedures, and any validity or reliability analyses so that the study can be replicated. The present report is also limited by the absence of a reported statistical reliability coefficient for the pretest/posttest instrument; future studies should document instrument validation and reliability procedures when such analyses are conducted.

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