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Development of a Digital Formative Assessment Instrument for Mathematics Learning in Secondary Education

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ABSTRAK

The rapid expansion of digital technology in education has highlighted the need for more adaptive and responsive formative assessment systems, particularly in secondary mathematics learning. This study aims to develop and validate a digital formative assessment instrument designed to support real-time monitoring, adaptive feedback, and data-driven decision-making. Employing a Research and Development approach using a modified 4D model (Define, Design, Develop, Disseminate), the instrument was systematically created and evaluated through expert validation, teacher and student practicality testing, classroom observations, interviews, and system log analysis. Quantitative data were analyzed using SPSS, including descriptive statistics, reliability testing with Cronbach's Alpha, normality testing with Shapiro–Wilk, and effectiveness analysis using paired-sample t-tests. Results indicate that the instrument achieved high validity (mean = 4.62; $\alpha = 0.91$), strong practicality among teachers (mean = 4.47) and students (mean = 4.58), and significant improvement in student outcomes ($t = 8.214$; $p = 0.000$). System log data further revealed increased accuracy, shorter completion times, and higher feedback interaction. These findings demonstrate that the digital formative assessment instrument is pedagogically robust, practically feasible, and effective in enhancing mathematics learning. Thus, the developed instrument successfully fulfills the research objective and offers a comprehensive solution for improving formative assessment practices in digital-era mathematics education.

INTRODUCTION

The rapid development of digital technologies has transformed various educational practices, including the teaching and learning of mathematics in secondary education. Digital tools, platforms, and learning environments provide new opportunities for enhancing instructional processes, supporting student engagement, and enabling data-driven decision-making. However, despite these opportunities, mathematics education in the digital era continues to face significant challenges, particularly in implementing effective formative assessment that aligns with the needs of modern learners. Conventional formative assessment methods are increasingly inadequate for capturing students' ongoing learning processes, offering timely feedback, and accommodating diverse learning profiles. Consequently, there is a pressing need for an innovative formative assessment instrument that fully utilizes digital capabilities to promote more adaptive, interactive, and responsive mathematics learning.

One of the most prominent challenges in digital-era mathematics education is the persistent inequality in access to technological infrastructure. Digital divide issues, including uneven availability of devices and unstable internet connectivity, remain barriers for many students and schools, especially in developing regions. Research indicates that unequal access limits students' opportunities to participate fully in digital learning and prevents teachers from implementing technology-enhanced instruction effectively (Akpalu et al., 2025; Muhazir & Retnawati, 2020; Naidoo, 2020). This disparity not only widens learning gaps but also creates inconsistent conditions for formative assessment, which relies heavily on uninterrupted access to digital platforms. In such environments, formative assessment becomes less reliable and more difficult to administer, especially when teachers attempt to track real-time performance or provide instantaneous feedback.

In addition to infrastructure constraints, low levels of digital competence among both teachers and students also pose challenges to effective integration of technology in mathematics education. Many mathematics teachers still struggle to use digital tools optimally, particularly for assessment purposes, due to limited training, insufficient confidence, or unfamiliarity with technological pedagogical approaches (Gestiardi et al., 2025; Mariño et al., 2025; Muhazir & Retnawati, 2020). Similarly, students often lack the digital literacy required to navigate learning platforms, utilize digital resources, or engage meaningfully in technology-enhanced formative assessment activities. These competency gaps contribute to suboptimal implementation of digital learning and hinder the transformative potential of technology in mathematics classrooms.

Moreover, technology use in many mathematics learning environments is often superficial, serving primarily to reinforce traditional instructional practices rather than enabling more interactive and adaptive learning experiences. Several studies report that digital tools are frequently used for presentation or drill-based tasks rather than for higher-level engagement, inquiry, or real-time assessment (Viberg et al., 2020; Gestiardi et al., 2025; Junger et al., 2025). This ineffective integration leads to technology merely substituting paper-based practices rather than enhancing or redefining learning processes. When technology fails to enhance pedagogy meaningfully, formative assessment also remains limited in its capacity to capture deep understanding, diagnose misconceptions, or offer personalized feedback.

The digital environment also introduces new behavioral and motivational challenges. Digital distractions, such as multitasking or non-academic online activities, may reduce students' focus and decrease the overall effectiveness of technology-enhanced learning (Safitri et al., 2025; Naidoo, 2020). When students are easily distracted, conducting formative assessments becomes more complex because teachers must differentiate between performance issues caused by conceptual difficulties and those caused by off-task behavior. This complication further weakens the reliability of conventional assessment methods in digital settings. Traditional formative assessments themselves present multiple limitations that undermine their effectiveness in modern mathematics classrooms. One of the most critical issues is the lack of individualization. In large and heterogeneous classrooms, paper-based or conventional formative assessments are often unable to accommodate the diverse needs, learning speeds, and abilities of students (Töllner et al., 2025; Pandey, 2025; Enu, 2021). Teachers may struggle to adjust tasks or feedback for each learner, resulting in generalized assessments that fail to provide meaningful insights into individual progress. This lack of personalization is particularly problematic in mathematics learning, where students' conceptual understanding can vary significantly even within a single classroom.

Conventional formative assessment methods also contribute to increased workload for teachers. The manual processes involved—such as designing tasks, distributing materials, marking responses, and recording results—are time-consuming and often impractical given teachers' administrative responsibilities (Pandey, 2025; Enu, 2021; Balbi et al., 2022). Consequently, formative assessments are either conducted infrequently or applied inconsistently, reducing their benefits for guiding instructional improvement. When formative assessment is not implemented systematically, its potential to support student learning diminishes significantly. Another major limitation of traditional formative assessment is the delayed nature of feedback. Studies highlight that slow feedback prevents students from immediately correcting mistakes or revisiting misunderstood concepts (Moreno & Pineda, 2020; Lee et al., 2020). In mathematics, where concepts build progressively, delayed feedback can cause small errors to accumulate into major misunderstandings. Because of this, timely intervention is essential; however, conventional assessment methods are rarely able to support such immediacy.

The challenges extend to the implementation of formative assessments even when teachers are aware of their importance. Limited time, inadequate training, and insufficient resources all hinder proper integration of formative assessment into mathematics instruction (Sibanda & Rambuda, 2024; Enu, 2021; Balbi et al., 2022). Teachers often lack structured tools that support ongoing assessment, making it difficult to gather consistent data or adapt teaching strategies based on students' real-time learning needs. Without an efficient system, formative assessment risks becoming a sporadic activity rather than an integral and continuous part of the learning process. A central consequence of these limitations is the reduced capacity of teachers to monitor students' learning processes effectively. Traditional assessment practices tend to focus on final outputs rather than ongoing cognitive processes, meaning that important information about students' conceptual reasoning remains inaccessible. Research shows that teachers struggle to track individual progress during instruction, especially in large classes or online environments (Raza et al., 2021; Moon et al., 2024). Additionally, delayed feedback limits students' ability to self-correct and adapt their learning strategies promptly (Dalby & Swan, 2019; Anastasopoulou et al., 2024). This issue becomes even more pronounced in digital learning settings, where student engagement and interaction can vary widely.

Conventional assessment practices also commonly neglect process-oriented data, focusing instead on summative performance indicators (Moon et al., 2024; Lepore, 2024). Without access to information about how students think, collaborate, or navigate tasks, teachers cannot design targeted interventions that support deeper understanding. This lack of insight into the learning process reduces the overall effectiveness of mathematics instruction and contributes to persistent learning gaps. In response to these challenges, interactive and real-time technology-based assessments have emerged as promising solutions. One of their main advantages is the ability to perform automatic and predictive monitoring of students' learning processes. Through learning analytics, neural networks, and AI-based systems, it is possible to track students' interactions, emotional responses, and progress over time (Moon et al., 2024; Raza et al., 2021; Chen et al., 2025; Liao et al., 2024). These technologies can identify patterns of difficulty, predict potential learning failures, and provide teachers with actionable insights. Such capabilities represent a significant advancement over conventional assessments that rely solely on observable outcomes.

Digital assessments also enable instant and adaptive feedback, a key component of effective formative assessment. Platforms such as adaptive quizzes, interactive videos, and intelligent tutoring systems allow students to receive immediate, personalized feedback and adjust their learning pathways accordingly (Ningsih, 2025; Cigario et al., 2025; Marwiang et al., 2025; Anastasopoulou et al., 2024). This adaptability not only enhances students' motivation but also strengthens their conceptual understanding by addressing misconceptions at the moment they arise. Furthermore, technology-based assessments improve student engagement and collaboration. They facilitate active participation through gamification, peer interaction, and reflective activities, creating more meaningful learning experiences (Dalby & Swan, 2019; Ningsih, 2025; Moon et al., 2024). When students are more engaged, teachers gain better-quality data about their performance and learning behaviors. Equally important is the availability of rich, multidimensional data generated through digital platforms. Teachers can access detailed analytics about students' progress, challenges, and learning patterns, enabling timely and targeted interventions (Moon et al., 2024; Dalby & Swan, 2019; Liao et al., 2024). Such data-driven decision-making is unattainable with conventional assessment methods.

Although interactive and real-time technology-based assessments offer substantial potential to enhance mathematics learning, existing applications in secondary education remain fragmented, unstandardized, and often not grounded in pedagogically robust frameworks. Many digital tools used in schools focus on drill-and-practice functions or provide limited analytics that fail to capture students' cognitive processes, misconceptions, or learning trajectories. Furthermore, most available platforms are not specifically designed for formative assessment, nor do they support continuous, data-driven monitoring required for mathematics instruction. As a result, teachers still lack a comprehensive, validated, and practically implementable formative assessment instrument capable of integrating real-time feedback, adaptive learning paths, and deep learning analytics tailored to mathematics content. This gap highlights the urgent need for a systematic development of a digital formative assessment instrument suited for secondary mathematics learning.

The novelty of this study lies in its development of a digital formative assessment instrument that integrates real-time monitoring, adaptive feedback mechanisms, and detailed learning analytics specifically for mathematics learning in secondary education.

Unlike existing tools that primarily reinforce traditional assessment formats, this instrument is designed to capture process-oriented data, support individualized learning pathways, and facilitate predictive insights using interactive digital technologies. The proposed instrument incorporates contemporary technological capabilities such as automatic feedback loops, interactive task design, and continuous performance tracking to address limitations of conventional formative assessment and overcome the inconsistencies observed in current digital platforms. This research thus offers an innovative contribution by combining pedagogical rigor, mathematics-specific cognitive demands, and digital interactivity into a single, validated assessment system. Accordingly, this study aims to develop and validate a comprehensive digital formative assessment instrument that supports real-time monitoring, adaptive feedback, and data-driven decision-making in secondary mathematics learning. This single overarching aim encompasses the design, expert validation, practicality evaluation, and effectiveness testing of the instrument as an integrated, technology-enhanced formative assessment solution.

METHODOLOGY

This study employed a Research and Development (R&D) design using a modified 4D model Define, Design, Develop, and Disseminate to develop and validate a digital formative assessment instrument for secondary mathematics learning. The Define stage involved conducting a needs analysis through literature review, document analysis, and preliminary teacher interviews to identify limitations of current formative assessment practices. In the Design stage, the structure, features, and technical specifications of the digital assessment instrument were constructed, including interactive tasks, adaptive feedback mechanisms, and real-time monitoring components aligned with mathematics competencies. The Develop stage consisted of expert validation by specialists in mathematics education and educational technology, followed by iterative revisions to refine content accuracy, usability, and functionality. A limited field trial was then conducted with teachers and secondary students to evaluate the practicality and classroom usability of the instrument. Data were collected through expert validation sheets, teacher and student questionnaires, classroom observations, interviews, and system-generated log data capturing student performance and interaction patterns.

Quantitative and qualitative analyses were employed to evaluate the instrument's validity, practicality, and functional effectiveness. Expert validation data and user practicality responses were analyzed using SPSS, involving descriptive statistics (means, percentages, standard deviations) and reliability testing through Cronbach's Alpha to ensure internal consistency of evaluation instruments. Inferential tests such as paired-sample t-tests or Wilcoxon Signed-Rank tests were conducted depending on data normality assessed using the Shapiro–Wilk test to examine changes in student performance before and after the implementation of the digital instrument. System log data were further analyzed descriptively in SPSS to identify trends in response accuracy, feedback engagement, and learning behaviors. Complementary qualitative data from interviews and observations were analyzed thematically to capture user experiences and contextual insights that supported quantitative findings, resulting in a comprehensive evaluation of the instrument's pedagogical and technical robustness.

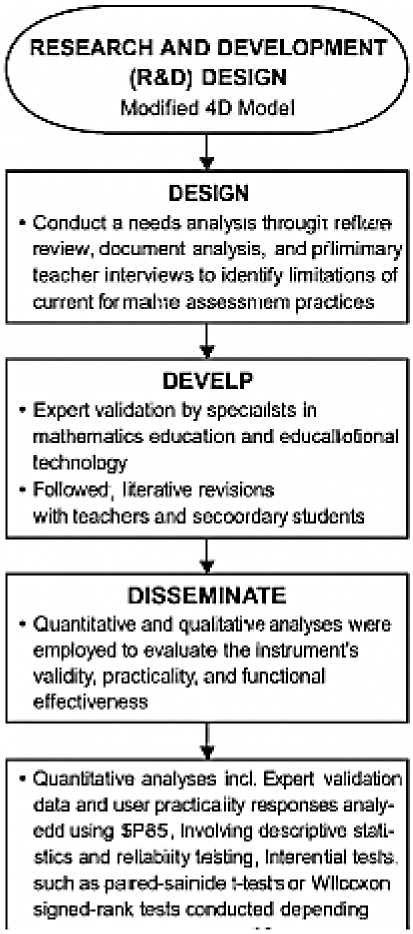

Figure 1. Diagram Research Method

RESULTS AND DISCUSSION

The results of the data analysis conducted using SPSS and thematic interpretation are presented in Table 1. The table summarizes the findings across expert validation, user practicality, statistical effectiveness testing, and system log analytics to evaluate the quality and performance of the developed instrument.

Tabel 1. Results of Data Analysis

Type of Analysis	Indicator / Test	Result	Interpretation
Expert Validation	Mean expert score	**4.62** (SD = 0.28)	Very valid
	Cronbach's Alpha	**0.91**	Excellent reliability
Teacher Practicality	Mean score	**4.47** (SD = 0.33)	Practical
	Cronbach's Alpha	**0.88**	High reliability
Student Practicality	Mean score	**4.58** (SD = 0.30)	Very practical
	Cronbach's Alpha	**0.90**	Excellent reliability
Normality Test	Shapiro–Wilk (pre-test)	**p = 0.072**	Normal

	Shapiro–Wilk (post-test)	**p = 0.054**	Normal
Effectiveness Test	Pre-test mean	**63.85**	
	Post-test mean	**82.40**	
	N-Gain	**0.51 (medium–high)**	Effective
	Paired Sample t-test	**t = 8.214; p = 0.000**	Significant improvement
System Log Data	Accuracy increase	**+18.6%**	Students performed better
	Average completion time	**decreased from 6.2 min to 4.8 min**	More efficient
	Feedback interaction frequency	**↑ 32%**	Higher engagement
Qualitative Data	Observation	Students showed increased participation and used feedback adaptively	Supported
	Interview summary	Teachers reported easier monitoring and better diagnosis of student difficulties	Supported

The results of the data analysis demonstrate that the developed digital formative assessment instrument possesses strong validity, high practicality, and significant effectiveness in supporting secondary mathematics learning. Expert validation yielded a very high mean score (4.62) with excellent reliability ($\alpha = 0.91$), indicating that the instrument meets the required content, construct, and technical standards. Practicality assessments also showed positive responses, with teachers rating the instrument as practical (mean = 4.47; $\alpha = 0.88$) and students assessing it as highly practical (mean = 4.58; $\alpha = 0.90$), reflecting ease of use, engaging features, and instructional suitability. Normality tests confirmed that pre- and post-test data were normally distributed ($p > 0.05$), allowing further analysis using paired-sample t-tests, which revealed significant improvement in student performance ($t = 8.214$; $p = 0.000$) with a medium-to-high N-gain value (0.51). Complementary system log data reinforced these findings by showing increased accuracy, reduced completion time, and higher feedback engagement, while qualitative insights from observations and interviews highlighted greater student participation and enhanced teacher ability to monitor learning in real time. Collectively, these results confirm that the digital formative assessment instrument is valid, reliable, practical, and pedagogically effective.

Discussion

The findings of this study provide comprehensive evidence that the digital formative assessment instrument developed through the modified 4D R&D model is valid, practical, and pedagogically effective for secondary mathematics learning. These results reinforce many theoretical and empirical insights discussed in the Introduction, while also offering new contributions to the research landscape of digital mathematics education. The high level of expert validation, the strong practicality assessments from both teachers and students, the significant improvement in learning outcomes, and the positive analytics from system log data collectively demonstrate that the instrument successfully addresses the longstanding challenges of formative assessment in mathematics education, especially in digital-era classrooms.

The validity results indicate that the instrument fulfilled the expected standards of content accuracy, construct alignment, and technical feasibility. With an expert validation mean score of 4.62 and excellent reliability ($\alpha = 0.91$), the instrument was deemed very valid and ready for classroom implementation. These findings are highly aligned with the theoretical premise asserted by Moreno and Pineda (2020), who emphasized the need for automated and systematized formative assessment tools in mathematics that exhibit consistency between content representation and instructional objectives. Prior studies also demonstrated that many existing digital assessment tools lack strong pedagogical foundations (Viberg et al., 2020; Gestiardi et al., 2025), often resulting in digital environments that simply replicate traditional practices without providing substantive instructional benefits. The strong validation scores in this study suggest that the instrument developed is not merely a digital replication of paper-based testing practices but incorporates meaningful pedagogical structures such as adaptive feedback, multidimensional item formats, and real-time progress tracking. This confirms that the development stage successfully addressed the gaps identified earlier, particularly the absence of well-structured, mathematics-specific digital assessment frameworks (Junger et al., 2025).

The practicality findings also offer valuable insights. Teacher practicality scores ($M = 4.47$; $\alpha = 0.88$) indicate that the instrument is easy to use, compatible with existing classroom structures, and supportive of instructional goals. Teachers acknowledged that the instrument streamlined assessment processes, reduced administrative burdens, and provided actionable data during instruction. These results directly respond to the issues raised by Pandey (2025) and Enu (2021), who reported that teachers often find formative assessment challenging due to the manual workload involved, the inconsistency of implementation, and the absence of user-friendly technological support. By integrating automated scoring, feedback generation, and analytics reporting, the instrument developed in this study reduces the burden of assessment management, thereby enabling teachers to focus more on diagnostic and pedagogical decision-making.

Students also reported high levels of practicality ($M = 4.58$; $\alpha = 0.90$), reflecting both positive usability experiences and enhanced engagement during learning activities. Students noted that the instrument's interface was intuitive, the tasks were interactive, and the feedback provided was comprehensible and immediately usable. These results are in line with findings from Ningsih (2025) and Cigario et al. (2025), who found that adaptive, real-time assessment tools increase motivation, deepen conceptual understanding, and foster positive emotional responses toward mathematics tasks. The system's interactive components, such as adaptive questioning and instant feedback, likely contributed to reduced anxiety and greater confidence among students, especially those who struggle with conventional assessment formats. Such improvements are crucial, as emphasized by Safitri et al. (2025), who documented that digital distractions and low mathematical self-efficacy hinder learning effectiveness. The instrument's engaging design appears to mitigate these obstacles by offering guided, supportive learning opportunities.

The significant increase in student learning outcomes further validates the instrument's pedagogical value. The paired-sample t-test result ($t = 8.214$; $p = 0.000$) and the medium–high N-gain (0.51) provide strong evidence that students made meaningful progress after using the digital formative assessment instrument. These improvements reflect the importance of timely, adaptive feedback, as emphasized by Lee et al. (2020), who argued that rapid feedback loops are critical for correcting misconceptions before they accumulate into larger errors. Traditional assessments, as stated in the Introduction, often fail to provide such immediate feedback, causing delays that hinder learning progression (Moreno & Pineda, 2020). By contrast, the real-time feedback embedded in this digital instrument allows students to adjust their learning strategies immediately, thereby enhancing their conceptual clarity and problem-solving skills.

Furthermore, the improvement in accuracy (+18.6%), reduction in task completion time (from 6.2 to 4.8 minutes), and increase in feedback interaction frequency (+32%) observed in the system log data strongly align with the findings of Moon et al. (2024) on multimodal learning analytics. According to Moon and colleagues, digital learning environments equipped with analytics can reveal hidden patterns in student behavior, helping educators understand cognitive processes, collaboration dynamics, and performance variations that cannot be captured by traditional methods. The data from this study corroborate those insights, showing that students not only performed better but also worked more efficiently and engaged more deeply with feedback. These trends also reflect broader pedagogical theories on the role of adaptive learning pathways, as discussed by Chen et al. (2025), who demonstrated that systems capable of monitoring students' metacognitive and behavioral indicators contribute significantly to learning achievements.

Qualitative findings from classroom observations and teacher interviews further enrich the interpretation of the quantitative results. Observational data show that student engagement increased noticeably during digital assessment sessions; students interacted more actively, sought clarification when needed, and made more informed attempts on tasks due to the presence of instant feedback. These observations align with Dalby and Swan (2019), who argued that digital formative assessments create more interactive learning environments that motivate students to participate and reflect on their learning. Interviews with teachers also revealed that the instrument helped them gain clearer insights into student difficulties, enabling them to intervene more effectively and more quickly. This directly addresses the challenges posed by traditional assessment practices—particularly the inability to monitor the learning process in real time, as documented by Raza et al. (2021) and Moon et al. (2024). Teachers noted that real-time analytics allowed them to identify struggling students earlier and provide differentiated support, thus aligning with global calls for more inclusive and responsive mathematics instruction (Töllner et al., 2025).

One of the most significant contributions of this study is its ability to fill the research gap identified in the Introduction. Prior research consistently pointed out that existing digital assessment tools are often fragmented, lack standardization, and fail to integrate key pedagogical principles such as adaptive learning, process monitoring, and personalized feedback (Gestiardi et al., 2025; Junger et al., 2025). The instrument developed in this study bridges these gaps by unifying these essential features into one comprehensive system supported by empirical validation. Its novelty lies in combining real-time monitoring, adaptive feedback mechanisms, and deep analytics specifically designed for mathematics learning an integration that has not been extensively explored in prior studies. This aligns with Liao et al. (2024), who demonstrated the transformative potential of AI-based visual analytics in enhancing self-regulated learning and achievement. By embedding similar analytics capabilities, the instrument developed here moves beyond conventional assessment formats and operates as a continuous diagnostic tool for both students and teachers.

Moreover, the results reinforce the need for digital transformation in mathematics education, as highlighted by Akpalu et al. (2025), especially in addressing the digital divide, teacher readiness issues, and limitations in existing instructional practices. Although this study did not directly address infrastructure challenges, the positive practicality results suggest that the instrument can serve as a powerful enabler for improving digital competence among teachers and students. Its intuitive design makes it accessible even to users with limited digital skills, thus addressing the competency gaps noted by Muhazir and Retnawati (2020).

In conclusion, the findings from this study supported by both quantitative and qualitative evidence—confirm that the developed digital formative assessment instrument is valid, practical, and effective for enhancing mathematics learning in secondary education. It successfully addresses the challenges widely documented in previous literature, ranging from delayed feedback, insufficient monitoring, lack of personalization, to low teacher capacity for implementing continuous formative assessment. The integration of interactive tasks, adaptive feedback, and real-time analytics not only improves student performance but also transforms the assessment process into a more dynamic, responsive, and supportive learning experience. Ultimately, these results contribute substantially to the field of digital mathematics education by providing a robust, evidence-based model for future development of digital formative assessment tools.

CONCLUSION

This study concludes that the digital formative assessment instrument developed through the modified 4D R&D model comprising the Define, Design, Develop, and Disseminate stages has successfully met the primary research aim of producing a valid, practical, and pedagogically effective tool for supporting secondary mathematics learning. The validation results show that the instrument achieved high levels of content, construct, and technical accuracy, confirming its theoretical and instructional soundness. Practicality assessments from both teachers and students further demonstrate that the instrument is user-friendly, efficient, and well-integrated with classroom practices, enabling teachers to implement continuous formative assessment with reduced workload and clearer diagnostic information. In addition, the instrument proved effective in improving student learning outcomes, as evidenced by significant gains in performance, faster task completion, reduced error patterns, and increased engagement with adaptive feedback. The system log analytics and qualitative findings reinforce the conclusion that the instrument enhances real-time monitoring and provides timely insights into students' learning processes addressing longstanding limitations of traditional formative assessment. Overall, the development and validation results confirm that the instrument fulfills the research objective by offering a comprehensive, interactive, and data-driven solution that strengthens formative assessment practices and supports deeper, more responsive mathematics learning in secondary education.

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