

A Comparative Study of Digital Bar Model Tools: Deepening Students' Understanding of Linear Equations

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Abstract: *This study compares three digital bar model tools—BarModelMath, Math Playground's Thinking Blocks, and PhET's Equality Explorer—to examine how each supports students' conceptual understanding of linear equations. Anchored in the Concrete–Pictorial/Representational–Abstract instructional approach, Realistic Mathematics Education, and Cognitive Load Theory, the study investigates how these tools facilitate visualization of algebraic relationships, relational reasoning, and cognitive load management. A comparative content analysis evaluated each tool's features, interactivity, feedback, support for symbolic notation, scope, and alignment with educational theories. Results indicate that BarModelMath and Thinking Blocks emphasize the representational stage through story-based and interactive bar modeling, enabling students to construct relationships and comprehend unknown quantities before encountering symbolic equations. In contrast, PhET's Equality Explorer places more importance on the abstract stage, integrating visual balance scales with algebraic symbols and allowing direct manipulation of variables and operations, bridging students to formal equation solving. The results suggest that sequencing instruction from contextualized, representational tools to abstract, symbolic simulations can strengthen conceptual understanding while reducing cognitive load. However, teacher guidance and locally relevant adaptation are crucial to ensure meaningful engagement and knowledge transfer. These findings highlight the potential of digital bar-model tools, when embedded in theory-informed pedagogy, can move students beyond rote procedures, promote interactive learning, and establish a strong foundation for higher-level algebraic reasoning.*

1. Introduction and Problem Statement

The linear equation is one of the foundational topics in algebra, and understanding its concept serves as a gateway to advanced mathematics such as calculus and trigonometry. In the Philippines, students encounter this lesson first in the 7th grade, as outlined in the Department of Education's MATATAG Curriculum Guide [1], marking a cognitive transition from concrete arithmetic operations to abstract algebraic thinking. However, students frequently struggle with such equations because abstract symbols, like letters for variables, obscure the relationships between quantities [2,3], and traditional "transpose" procedures emphasize rote manipulation over conceptual understanding. This shallow understanding may carry over into later learning, where variables are used extensively in more complex mathematical domains.

To address this gap, curriculum designers in the Philippines have mandated the use of the bar model in teaching simple linear equations [1], as it is an effective tool for bridging arithmetic and algebraic thinking. Bar modeling offers a concrete visual approach to demonstrate algebraic relationships, making the structure of linear equations more accessible and meaningful to students [4]. Especially in conjunction with contextualized word problems, these illustrations help learners interpret variables as quantities rather than abstract symbols, supporting the development of relational understanding and mathematical reasoning [5]. The integration of technologies enhances this approach further. Digital bar model tools provide interactive, dynamic representations of equations. They allow students to manipulate elements such as blocks, weights, and labels and immediately see the effects on the model. Guided by Cognitive Load Theory (CLT), well-designed

digital tools can reduce extraneous demands and free students' working memory to focus on core concepts. Research shows that load reduction instruction significantly enhances students' motivation, engagement, and achievement in mathematics by easing cognitive strain [6]. When designed with principles of the Concrete–Pictorial/Representational–Abstract (CPA/CRA) progression and grounded in Realistic Mathematics Education (RME), such tools can support more profound and connected learning experiences.

This study compares three digital bar-model tools—BarModelMath, Math Playground's Thinking Blocks, and PhET's Equality Explorer—to evaluate how each aligns with educational theories and supports the conceptual understanding of linear equations. By focusing on features, interactivity, scope, and theoretical alignment, the analysis aims to inform how technology can increase students' mathematical content knowledge through enhanced visualization and interaction.

2. Review of Related Literature

This study is grounded in two complementary learning theories—Realistic Mathematics Education and Cognitive Load Theory—alongside the Concrete–Pictorial/Representational–Abstract instructional approach, which is informed by Bruner's Theory of Cognitive Development. Together, these frameworks suggest that digital bar model tools should provide clear representational scaffolds linking concrete contexts to algebraic form, let models emerge from realistic problem situations, and be designed to reduce cognitive strain among learners.

2.1. Concrete–Pictorial/Representational–Abstract Progression

CPA/CRA outlines a sequence from concrete experiences with manipulatives through pictorial illustrations to abstract symbolic reasoning [7]. In this sequence, bar models serve as the pivotal representational stage. They are pictorial/diagrammatic tools that link physical quantities to algebraic forms. Research on CPA/CRA indicates that providing visual models improves students' ability to grasp algebraic relationships before they encounter symbols. It was found in [8] that CRA-based instruction improved students' representational ability in algebra, while it was reported in [9] that there were significant gains in problem-solving when bar models were used as visual supports. These findings highlight the use of bar models as a vital bridge that supports concrete-to-abstract mapping for conceptual understanding.

2.2 Realistic Mathematics Education

RME is based on the principle that mathematics should be taught as a human activity grounded in real-life contexts. Central to RME is the idea that students should not be passive recipients of mathematical rules but should develop understanding through guided reinvention—constructing mathematical knowledge by modeling meaningful problem situations [10]. Bar models function well within this framework, acting as informal tools that emerge from contextual problem-solving and evolve into more formal representations such as algebraic equations. It was demonstrated in [11] that applying RME principles through modeling strategies like bar diagrams enhanced the mathematical competence of students with learning difficulties. Similarly, [12] underscored that bar modeling within authentic contexts supported deeper and more lasting understanding. From this point of view, digital bar-model tools should embed problems in story-like contexts so that students can naturally invent or refine bar representations.

2.3 Cognitive Load Theory

CLT explains how instructional design can optimize learning by managing the limitations of working memory through three types of cognitive load: intrinsic load from task complexity, extraneous load from poor design, and germane load related to schema construction [13]. It was found in [14] that scaffolding in digital learning environments reduced cognitive load and improved student performance. Similarly, it was reported in [15] that multimedia-based discovery learning designed with CLT principles enhanced mathematical learning efficiency and performance, while decreasing mental effort. These findings support the CLT perspective that well-structured visual and representational supports—such as integrated visuals, worked examples, scaffolding, and feedback—can reduce the mental demands of complex algebraic concepts and help students build more durable knowledge structures. Therefore, integrating bar models with interactive technology can help students understand linear equations with less confusion over abstract symbols.

3. Methodology

This study employed a comparative content analysis [16] of three widely available digital bar model tools relevant to teaching linear equations. BarModelMath, Math Playground's Thinking Blocks, and PhET's Equality Explorer were selected based on their accessibility, use of bar representations, and connection to the target lesson. A key criterion was that all three tools are completely free to use, removing financial barriers for both teachers and students. Exploring such free tools can be especially helpful in the Philippines, where many teachers reportedly struggle with the lack of teaching resources and technology in the classroom [17].

The analysis was organized into four categories: (1) features, (2) interactivity and feedback, (3) scope, and (4) theoretical alignment. Specific evaluation indicators for each include degree of contextualization, type of interactivity, nature of feedback, presence of symbolic notation, and alignment with CPA/CRA, RME, and CLT. Tools were rated on these indicators using a qualitative scale (High, Moderate, Low, None), allowing the study to present both descriptive insights and comparisons. The authors contend that qualitative ratings are more meaningful than quantitative ones, since the indicators are not uniform (i.e., not all measure alignment). Data were collected by the primary author through direct interaction with each tool, systematic recording of functionalities, and a review of developer-provided descriptions.

4. Results and Discussion

This chapter presents the findings from the comparative content analysis of three digital bar modeling tools. Sections 4.1 to 4.3 detail the features, interactivity, feedback, scope, and theoretical alignment of each tool, while Section 4.4 synthesizes these outcomes through a comparative matrix with qualitative descriptions and ratings. The analysis highlights how the tools support different stages of algebra learning, from contextualized problem-solving to symbolic abstraction, and identifies both their complementary strengths and practical challenges.

4.1 BarModelMath

BarModelMath is a web-based platform offering a variety of math games across different topics, such as arithmetic, fractions, ratios, decimals, and early algebra. The digital tool is developed by iSingapore Math LLC and is available at this link: <https://barmodeling.com/>. This section will examine its key features, interactivity and feedback mechanisms, content scope, and alignment with educational theories.

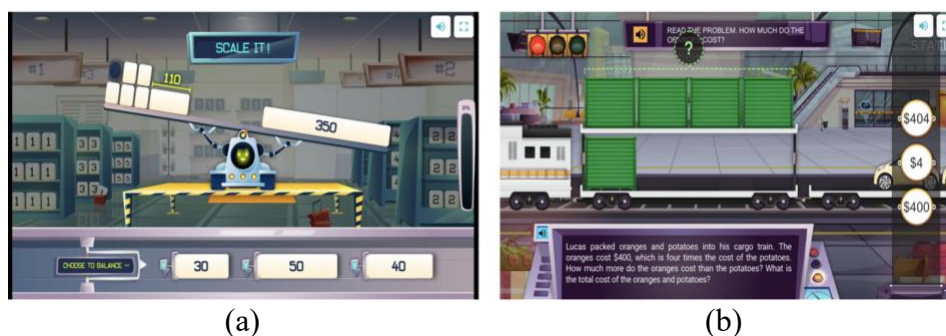


Figure 4.1 (a) Sample multi-step activity from Bar Model Scale; (b) Sample contextualized problem from Bar Model Express

4.1.1 Features

There are two bar model-based activities: Bar Model Express and Bar Model Scale. In Bar Model Express, learners are given a word problem alongside a train illustration. Each car in the train contains cargo or passengers represented as square boxes, and students are prompted to determine the values of these quantities based on the relationships described in the scenario, as shown in Figure 4.1(b). In the Bar Model Scale, students interact with a visual weighing scale, where each side contains bars. The task is to identify the numerical values that balance both sides, as illustrated in Figure 4.1(a). Across both activities, the bar models are pre-constructed. Students do not create the bars but rather interpret their structure and compute missing quantities. Additionally, values are not manually inputted, as students select their answers from given multiple-choice options. Other games on the site cover a wide range of topics and do not necessarily use bar models, offering varied visual formats such as grids, tables, or number lines.

4.1.2 Interactivity and Feedback

In both Express and Scale, students select numerical answers in response to visual bar prompts. The system evaluates entries in real time and gives immediate feedback, allowing learners to retry if they get incorrect answers. In the Scale activity, learners test multiple values until the bars on both sides balance. Audio narration and highlighted cues help guide students through each stage, focusing attention on the bar model interpretation. The tasks are tightly structured because there is no open text entry, only pre-set answer choices, and users cannot construct models freely. This design heavily scaffolds the conceptual reasoning about quantities rather than procedural construction.

4.1.3 Scope

The mathematics in BarModelMath is suitable for upper-elementary and lower-secondary-level learners. While the platform does not involve symbolic linear equations or the use of variables, several bar model tasks relate to the logic underlying linear equations, particularly in the form of unknown quantities in additive or multiplicative relationships. These scenarios covertly mirror the structure of equations like " $x+a=b$ " or " $ax=b$," with students manipulating only numerical quantities without the presence of variables.

4.1.4 Theoretical Alignment

BarModelMath aligns with the representational stage of CPA/CRA. Since bar models are already drawn, students focus on mapping quantities onto them by interpreting the model. This supports the transition from concrete to abstract by situating unknowns in a visual, contextual form.

In terms of RME, the platform embeds mathematical tasks in contextualized scenarios, as seen in Figure 4.1(b). For example, learners are not solving symbolic problems but engaging with hypothetical situations involving trains, passengers, or cargos. The contexts are relatable, inviting learners to reinvent mathematical structures through guided reasoning. Finally, the platform reflects CLT by providing fixed bar models and focusing tasks narrowly on identifying relationships and values. This depicts that the tool reduces the extraneous load. No writing or complex navigation exists, which makes learners concentrate on the math relation. Additionally, feedback is immediate and integrated into the graphic, thus students control the cognitive flow. However, because BarModelMath limits students to selecting answers rather than constructing, it may not fully engage them in deeper problem-solving. Without variables or symbolic equations, the modeling tool may prepare thinking indirectly but does not provide learners the opportunity to practice algebraic notation.

4.2 Math Playground's Thinking Blocks

Math Playground's Thinking Blocks provides modeling tools and themed modules, each broken into levels such as Part-Whole, Compare, and Two-Step. The digital tool was created by Math Playground LLC, which was founded by Colleen King in 2002, and is available at this link: <https://www.mathplayground.com/thinkingblocks>. This section will explore its main functionalities, the nature of its interactivity and feedback, its content range, and how it aligns with established learning theories.

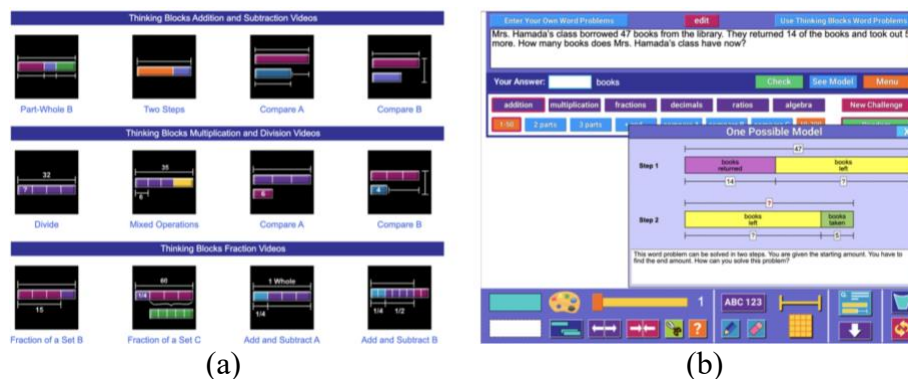


Figure 4.2 (a) Video modules on various topics to support student understanding of bar models; (b) Thinking Blocks tool featuring a word problem generated by the platform

4.2.1 Features

In Part-Whole problems, students model situations where a total is split into parts or parts are combined into a whole. Compare problems involve identifying differences between quantities, such as one amount being more or less than another. Two-step problems require students to model and solve problems that involve two sequential operations. The platform includes structured problem sets and a "Thinking Blocks tool," as seen in Figure 4.2(b), where students can either solve a provided problem or create their own. When solving problems provided by the platform, the tool allows students to model the relationships using draggable blocks, label them, and then check whether their answers are correct.

4.2.2 Interactivity and Feedback

Students interact with the platform by dragging blocks into a workspace, labeling known and unknown values, and typing numerical answers, not by selecting from multiple-choice options.

It is more open-ended than BarModelMath since students can actively create the bar model using the Thinking Blocks tool, as illustrated in Figure 4.2(b). However, if students input their own problems, the tool does not validate answers. It would only be a purely drawing/labeling tool. Students must then solve the equations themselves. This freedom encourages student generation but relies on teacher oversight or self-checking to ensure accuracy. Nonetheless, when working with built-in problems, the system checks model correctness at each step and gives real-time feedback. This process is scaffolded and includes optional video tutorials, like those shown in Figure 4.2(a). The interactivity supports students in actively constructing a model rather than passively interpreting one.

4.2.3 Scope

Thinking Blocks is suited for upper elementary to junior high school students. It includes basic operations, fractions, decimals, ratios, and proportions. Although the models closely mirror linear structures like "*total = part + part*" or "*larger = smaller + difference*," the tool does not use variables or symbolic notation. Unknown values appear as a blank or a box until solved. The focus remains on understanding the relationships via the bar model and reinforcing the conceptual groundwork of algebra without teaching equations involving variables.

4.2.4 Theoretical Alignment

Thinking Blocks strongly reflects CRA and RME pedagogies. It sits firmly in the pictorial/representational stage, where learners draw the bars themselves, linking story context to math structure. Letting students invent their models and real-world scenarios, like height and sharing problems, is a key principle of RME. The system's design also reduces extraneous load by breaking tasks into clear steps and providing automated feedback for each action. It clearly aligns with CLT, which suggests that using a modeling progression instead of jumping straight into abstract symbols frees up cognitive capacity and allows students to focus more on sense-making. However, it does not guide the learners into writing linear equations. Thinking Blocks requires students to perform the final arithmetic operations without algebraic symbols. Thus, while the representational link is strong, it stops short of formal algebraic abstraction.

4.3 PhET's Equality Explorer

PhET's Equality Explorer is a simulation that uses a virtual balance scale to help students develop an understanding of equality through direct visual manipulation. Unlike the previous tools, it introduces actual algebraic variables and equations explicitly. The digital tool was designed by PhET Interactive Simulations, a project founded by Carl Wieman in 2002, and is available at this link: https://phet.colorado.edu/sims/html/equality-explorer/latest/equality-explorer_all.html. This section will discuss its main features, how students interact with it, the kind of feedback it gives, the topics it covers, and how it fits with learning theories.

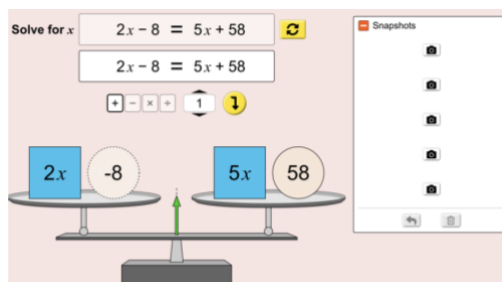


Figure 4.3 Sample activity from the Solve It mode

4.3.1 Features

The simulation includes five modes: Basics, Numbers, Variables, Operations, and Solve It. In the Basics mode, students drag identical shapes onto both sides of a scale to observe balance or imbalance. The Numbers mode introduces numerical weights labeled with whole numbers, allowing learners to explore numerical equality. In the Variables mode, students work with a square block labeled "x" alongside number blocks to visually represent and manipulate algebraic expressions. Operations mode allows learners to apply mathematical operations, such as adding or removing blocks from both sides, to mimic algebraic transformations. In the Solve It mode, illustrated in Figure 4.3, students encounter equation-solving tasks such as one-step and multi-step linear equations, including those with variables on both sides. Learners do not draw their own models but construct relationships by dragging and modifying visual objects.

4.3.2 Interactivity and Feedback

Students interact by dragging blocks and variable pieces to either side of a balance scale and adjusting values using on-screen tools. The scale dynamically tilts or balances based on the mathematical equivalence of each side. A symbolic equation updates automatically with each move, bridging visual and algebraic representations. Students must manually balance the scale through trial and error because there is no built-in hint system or correctness confirmation, except for what can be inferred from the balance and equation display. On the contrary, the Solve It mode provides feedback to students once they get the correct answer. A snapshot tool is also available, allowing students to record their current model for later reflection. The nature of this tool emphasizes exploration, as students discover algebraic principles, like adding or subtracting the same amount to both sides, through direct manipulation.

4.3.3 Scope

Equality Explorer is suited for upper elementary to high school students and covers key algebra concepts such as variable representation and equation solving. It supports one-step and two-step equations, negative weights for subtraction, variables on both sides, and fractions. Tasks in Solve It mode, as shown in Figure 4.3, involve formal equations typically found in algebra textbooks. Unlike the other two tools, it moves from pictorial representations like object balance to abstract symbolic equations within a single platform.

4.3.4 Theoretical Alignment

This simulation bridges the representational and the abstract in real time, embodying the CRA transition in an integrated way by combining visual balance scales, labeled blocks and bars (representational) and live equation updates (abstract). Unlike tools that simply present problems for solving, this simulation allows students to construct and manipulate mathematical relationships actively. Through the lens of Realistic Mathematics Education (RME), students engage in meaningful exploration by adjusting quantities in a dynamic environment that makes equivalence tangible, reflecting the principle of guided reinvention. However, it lacks contextual word problems. It operates in a symbolic/visual space rather than a narrative context. From a CLT viewpoint, the cognitive effort is better managed in the simulation through a clean layout, consistent visual logic, and immediate visual feedback. In contrast, because there are no hints or explicit instructions, learners must manage intrinsic and germane load independently, which may benefit exploratory learning but pose challenges without teacher guidance.

4.4 Comparative Synthesis of the Digital Bar Model Tools

Table 4.4 Comparison and Ratings of the Three Digital Bar Model Tools

Criterion/ Indicator	BarModelMath	Thinking Blocks	PhET's Equality Explorer
Contextualization	High – Story-based scenarios, e.g., trains carrying cargo or passengers	High – Everyday word problems, e.g., borrowing and returning books or comparing quantities	Low – Abstract balance tasks, e.g., solving equations such as $2x - 8 = 5x + 58$
Interactivity	Low – Pre-drawn bars; students select multiple-choice answers	High – Drag-and-drop blocks; students construct and label models	High – Balance-scale interactions; students drag weights or variables and apply operations
Feedback	High – Immediate feedback; visual cues confirm correctness	Moderate – Real-time feedback; provided problems supported but none for self-created	Moderate – Dynamic feedback; scale tilts and equations update but few direct hints
Symbolic Notation Support	None – No symbolic notation; problems remain numeric with blanks	None – No symbolic notation; unknowns shown as empty boxes	High – With symbolic notation; variables and equations used explicitly
CRA/CPA Alignment (in terms of proximity to Abstract)	Low – Pictorial; model reading with pre-drawn bars	Low – Pictorial; model building through block construction	High – Pictorial to Abstract; combining visual scale with algebraic symbols
RME Alignment	High – strong use of story contexts	High – students may generate their own contextual problems	Low – tasks not embedded in real-life narratives
CLT Alignment	High – scaffolding reduces extraneous load	Moderate – stepwise feedback but added intrinsic load from labeling	Moderate – clear visuals but limited guidance increases intrinsic load

Table 4.4 summarizes the findings by comparing BarModelMath, Thinking Blocks, and PhET's Equality Explorer across contextualization, interactivity, feedback, symbolic notation, and theoretical alignment. The matrix highlights their complementary strengths. BarModelMath and Thinking Blocks scored high on contextualization by situating problems in story contexts and everyday word problems, while Equality Explorer was rated low in this area, as it moves learners toward abstraction without a real-world story or application. Interactivity was low in BarModelMath, since students mainly select answers from pre-drawn bars, but high in Thinking Blocks and Equality Explorer, where students construct and manipulate models.

BarModelMath offers guided story word problems like trains carrying passengers, while Thinking Blocks allows students to model everyday scenarios such as borrowing and returning books. Equality Explorer, by contrast, presents algebraic tasks like $2x-8=5x+58$ in a balance-scale format, linking visual and symbolic representations without narrative context. These distinctions illustrate how each tool targets different dimensions of algebraic understanding, from interpreting quantities in real-world and hypothetical situations to manipulating abstract symbols.

At the same time, the tools present practical challenges. Symbolic notation support was absent (none) in BarModelMath and Thinking Blocks but high in Equality Explorer, while CLT alignment ranged from high (BarModelMath, due to reduced extraneous load) to moderate (Thinking Blocks and Equality Explorer, due to intrinsic load from labeling or minimal guidance). All are designed in English with generic cultural contexts, limiting their relatability for Filipino learners, and each requires teacher guidance to ensure students engage conceptually rather than treating tasks as puzzles. Overall, this shows that the tools serve different but complementary purposes, highlighting their potential when integrated thoughtfully into instruction.

5. Conclusion

This comparative study found that digital bar-model tools vary in how they deepen understanding of linear equations, each aligning with different instructional stages. BarModelMath and Thinking Blocks emphasize representational learning. Students interpret or construct bars within story problems, thus solidifying the idea of unknown parts and equivalence before encountering symbols. PhET's Equality Explorer emphasizes the abstract level. Learners directly manipulate " x " and operations on the balance scale, bridging to formal equations. This sequencing highlights the importance of matching tools with students' learning stages, consistent with the CPA/CRA progression, RME's focus on contextualized modeling, and CLT's emphasis on reducing cognitive load.

For Philippine mathematics education, utilizing these tools can help increase students' content knowledge through technology. By moving away from rote procedures toward interactive visualization, students may develop stronger conceptual schemas for equations. Instructional sequencing should deliberately begin with contextualized bar model tools such as BarModelMath and Thinking Blocks to build representational understanding, and then transition to Equality Explorer to foster abstraction and symbolic reasoning. However, technology alone is not a remedy. Active teacher mediation is essential to ensure that students interpret models meaningfully, while localized context design, such as the use of Filipino names, places, and culturally relevant problem scenarios, can enhance engagement and comprehension.

Future research, reflecting the limitations of this study, could involve classroom-based or quasi-experimental studies comparing students' performance on linear equations after using different tools or instructional sequences. Beyond achievement outcomes, such work might also examine student attitudes, motivation, and engagement, while incorporating teacher and student perspectives through surveys or interviews to capture usability and perceived benefits. Subsequent studies may further employ quantitative approaches to complement this qualitative analysis, providing measurable evidence to strengthen and extend the findings. Together, these directions would validate the effectiveness of digital bar-model tools and guide their localized development for Philippine classrooms. When integrated with theory-informed pedagogy, these tools hold promise for making algebra more accessible and meaningful, thereby strengthening students' foundation in higher mathematics.

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