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An advanced operating environment for mathematics education resources

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The potential of information technology (IT) in education modernization has been widely acknowledged. Among the broad efforts for advancing education IT, digital education resources continue to receive a high level of attention, with the goal of making high-quality education resources pervasively accessible anytime and anywhere. Unfortunately, the amount of such high-quality resources is still limited, particularly those suitable for mathematics education [1]. General expectations for high-quality digital mathematics education resources (MERs) include interactivity, openness, and transparency, all of which benefit enhancing the sustainability of MERs [2]. In this case, openness of an MER refers to the resource being easily edited and extended; transparency means that users have convenient access to the original development process of the resource. With these features, MERs can be continuously improved and augmented according to users' individual needs. The development and utilization of such MERs often rely on the deployment of a specialized "software or platform", which is commonly referred to as the "operating environment (OE)".

In elementary mathematics education, several existing OEs have been widely adopted. The most frequently utilized are popular and e-book compilation software, such as PowerPoint and iBooks Author [3]. However, these software packages are not specifically designed for mathematics education. Consequently, such tools often lack content-level deep interactivity, which is strongly desired by educators and learners, as well as fail to offer adequate domain-specific support. Various empirical studies have demonstrated the insufficiency of such OEs in conducting mathematics education [4]. Owing to the powerful function of mathematica, the computable document format (CDF)[1)] has been extensively deployed to develop MERs. CDF highlights easy interactivity for resources, empowering users to deliver contents and produce results live. Although the resources are interactive, they are difficult to edit and extend because these require the user's ability to program in mathematica. Another popular OE is the dynamic geometry system (DGS), which meets the requirements of interactivity and openness, thereby satisfactorily fulfilling a large amount of teaching and learning tasks and earning itself favorable reviews from practitioners. However, DGS still lacks other

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1) http://www.wolfram.com/cdf.

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critical functions for instructive support, such as the ability to carry out geometry proofs and symbolic computations. DGS resources exhibit low transparency because a user must navigate a complex operation process to trace the original development process of a resource. Finally, DGS requires a complicated set of steps to operate.

OEs are critical to the development and utilization of MERs. In this article, we propose a novel OE design for MERs that is user-friendly, specialized, and extensible. In order to specify the system architecture clearly, we propose a cascading-free data structure for the system design, along with certain key implementation technologies, which are introduced for knowledge enhancement, intelligent drawing, and automated reasoning. Based on the proposed system design and key implementation technologies, we develop a new OE for MERs known as the super sketchpad (SSP).

System design. The system architecture is displayed in Figure 1. The first criterion is to develop a user friendly OE. The main users of the OE include teachers and students. In order to attain this goal, the OE should be easy to operate in a manner resembling the operation paradigm of instructive drawing and writing on a physical blackboard as far as possible. The second criterion is specialization. The OE should fully support mathematics education. Teaching is discipline specific; therefore, the OE should provide not only general functions but also specialized domain support for instructing mathematics concepts. The third criterion is extensibility. It is impossible for a set of functions to meet the dynamically evolving teaching needs of individual instructors; therefore, the OE should be constructed in an extensible and adaptive manner.

Cascading-free data structure. The DGS treats geometric relationships between objects as the system architecture in order to maintain objects interdependence. In these systems, the relationships can easily become highly complicated when the number of included objects increases or the intent behind creating a drawing is ambiguous.

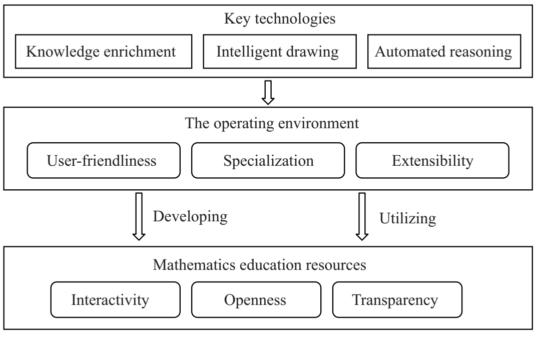

Figure 1 System architecture.

In fact, all objects, namely geometric graphs, formulas, and text, can be represented as visual data. Once a new object is created, the OE provides a means of data visualization, such as creating points A, B for displaying coordinates (a, b), (c, d), or creating a segment line AB related to the data (a, b, c, d). The data may be independent variables with a large value range or random variables based on the setting conditions, or values obtained by measuring geometric objects or evaluating expressions. When changing data values, all related objects will be updated accordingly; thus, all objects are directly associated with the corresponding data. In order to support this feature, two lists are built into the OE for data management, namely a data list and another object list. If a newly created object is associated with new variables, these variables are added to the data list and considered as parameters of the new object. Further details are available in Appendix A.

Knowledge enrichment technology. Based on the concept of knowledge enrichment [5], we establish a domain-specific language for mathematics knowledge (DSL-MK) by formally representing each piece of mathematics knowledge by its compositions and construction rule. We further establish a DSL-MK interpreter to translate a formal representation into its corresponding natural language, visualization, and algebra representations. Equipped with the DSL-MK and interpreter, the OE can retrieve the knowledge element and its parameters according to users' input, analyze the construction relationships, calculate the algebra data of the element involved, and finally visualize the element. We refer to this type of technology as "knowledge enrichment technology". With such technology, users can efficiently develop high-quality personalized MERs and make these resources sustainable.

Intelligent drawing technology. The effectiveness of the human-computer interaction (HCI) is highly important in computer systems. Context awareness technology is an effective means of promoting the intelligence of HCI [6]. In the current DGS, users must frequently click on toolbar buttons or menu items to draw basic geometric graphs. Such user interaction not only makes the drawing inefficient but also increases users' operational burden and visual overhead. To address this problem, we propose an intelligent drawing algorithm that is context aware. According to the construction conditions of each type of geometric graph, the algorithm establishes the matching relationships between graphs and selects a corre-

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sponding threshold. When users draw graphs with mouse clicks, double clicks, and drags, the algorithm extracts the graph context within the current drawing environment in real time. When current operations and part of the graphs' context satisfy one of the matching models and the corresponding threshold, the algorithm immediately recommends the next graph as an automatic suggestion for the next graph drawing step. The details of this algorithm are provided in Appendix B. With this algorithm, users can accurately and efficiently draw more than 20 types of geometric graphs, without any need for clicking on toolbar buttons or menu items. Such an operational design aims to mimic closely the traditional paradigm of drawing on a conventional blackboard in chalk.

Automated reasoning technology. In geometry, automated reasoning can both prove and discover geometry problems, which is highly useful in mathematics education [7]. In order to solve elementary geometry problems, we proposed several automated reasoning methods based on geometric invariants [8]. OEs that are equipped with such reasoning methods become even more powerful.

Super sketchpad. Based on the proposed system design and key implementation technologies, we develop an MER operating environment known as the SSP, which includes rich functionalities for meeting all teaching and learning requirements. It has been deployed in over 10000 schools for elementary mathematics education, and has received highly positive assessments. The details of the SSP are available in Appendix C.

Experiments. The details of our experiments are available in Appendix D. Experiment 1 demonstrates that the SSP supports a comprehensive set of needs in the teaching and learning of elementary mathematics, whereas experiment 2 proves the extensibility of the SSP. In experiment 3, utilizing the usability testing and evaluation model for educational software, we evaluate the SSP by means of the switching count (SC) of the menu, toolbar, and drawing area, operating amount (OA) and operating easiness ratio (OER). We furthermore compare these metrics with the corresponding measures of the geometer's sketchpad (GSP), which is currently the most popular OE for MERs. The experimental cases involve three practical mathematics teaching examples (Figure D2 in Appendix D). The experimental data (Tables D4, D5, and D6 in Appendix D) indicate that, on average, SSP reduces the SC to 1/5 of that of GSP, OA to 1/3 of that of GSP, and OER to 72% of that of GSP. The experimental results collectively demonstrate user-friendliness, domain support for mathematics education, extensibility, and efficiency of SSP in comparison with state-of-the-art systems.

Conclusion. In this article, we proposed a novel OE design for MERs that is user friendly, specialized, and extensible. We furthermore proposed a cascading-free data structure, making the system architecture more efficient. A series of key implementation technologies were additionally introduced to attain a high level of system usability, including knowledge enhancement, intelligent drawing, and automated reasoning. Based on these system elements, we implemented an OE for MERs known as SSP, which can meet all mathematics teaching and learning requirements. SSP has been widely deployed in classrooms for elementary mathematics education, and has been favorably reviewed by its mass end users. By means of empirical experiments, we demonstrated the user-friendliness, specialization, extensibility, and efficiency of SSP for MERs.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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