HNUE JOURNAL OF SCIENCE
Educational Sciences 2025, Volume 70, Issue 4, pp. 144-154
This paper is available online at http://hnuejs.edu.vn/es
DOI: 10.18173/2354-1075.2025-0078

APPLICATIONS OF COMPUTER ALGEBRA SYSTEMS IN TEACHING MATHEMATICS

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Received December 15, 2024. Revised July 17, 2025. Accepted July 30, 2025.

Abstract. The application of Information and Communication Technology (ICT) in education, particularly in Mathematics teaching, is an irreversible trend, as emphasized in the 2018 Mathematics curriculum. This paper presents the results of theoretical research on the use of Computer Algebra Systems (CAS) in teaching mathematics, including their historical development, potential, and significant pedagogical implications. Alongside theoretical exploration, the authors conducted practical investigations, summarizing experiences with CAS, exemplified by the Wolfram Alpha system. Based on these findings, several strategies for integrating CAS into teaching are proposed. Initial experiments show these approaches are feasible and yield positive results, promising effective implementation in practice.

Keywords: information and communication technology, computer algebra systems, Wolfram Alpha.

1. Introduction

Against the backdrop of globalization and international integration for each country, the development of ICT alongside the practical demand for using mathematics to address real-world issues has brought about new opportunities for teaching mathematics through the integration of information technology in teaching.

In Vietnam, the 2018 Mathematics curriculum has identified the mathematical competencies that students need to cultivate and develop. These competencies include the ability to think mathematically and reason, the ability to model mathematical problems, the ability to solve mathematical problems, the ability to communicate mathematically, and the ability to use tools and materials for learning mathematics. Integrating technology into teaching has become a crucial component of the teaching process, serving as one of the effective methods directly contributing to the development of the ability to use tools and resources for learning Mathematics, while simultaneously supporting the development of the other mentioned competencies within an appropriate teaching scenario.

In the realm of Mathematics Education with computer support, Computer Algebra Systems (CAS) are emerging as an essential tool and standard in teaching and learning Mathematics (Ardıç & İşleyen, 2018 [1]). Synthesizing various studies, Ardıç and İşleyen have indicated that instructional activities conducted through CAS influence students' levels of perception, problem-solving skills, academic achievements, computational skills, mathematical reasoning, and overall attitudes toward Mathematics (Ardıç & İşleyen, 2018 [1]). Similar findings have been underscored in other research studies (Buteau et al., 2010 [2]; Marshall et al., 2012 [3]) that delve into teaching activities carried out through CAS. These outcomes suggest that, through CAS, students engage with Mathematics with a deeper and enhanced understanding, improving their self-learning capabilities and overall competency. CAS amplifies students' motivation towards Mathematics, enabling them to tackle more challenging real-world mathematical situations efficiently. It simplifies complex scenarios, aligning with the needs of 21st-century professional domains. However, concerns persist regarding the inappropriate use of CAS, potentially leading to a decline in students' numerical skills (Alhumaid, 2019 [4]) and contributing to issues of distraction during class time (Ditzler, 2016 [5]).

In the context of Vietnamese education, several studies accessible to the authors have initially explored the application of CAS in mathematics instruction. Pham Huy Dien (2002 [6]), Phan Duc Chau (2005 [7]), Tai PA & Giang NN (2015 [8]), Hanh PM & Giau TTN (2019 [9]), Nga NT (2024 [10]) implemented MAPLE in teaching calculus-related topics, demonstrating the potential of CAS in supporting computation and visualizing mathematical content. More recent studies (Giang DT, 2024 [11]; Trung LTBT et al., 2024 [12]) have also begun to incorporate online CAS tools such as Wolfram Alpha and Microsoft Math Solver to support students' learning processes. However, these studies primarily remain at the level of tool demonstration and have yet to deeply explore the pedagogical potential of CAS in high school mathematics teaching and learning.

In an era that demands "coexistence" with technology, especially with CAS, the research questions are succinctly summarized as follows: Why should CAS be integrated into the teaching of Mathematics? How can CAS be effectively utilized in teaching Mathematics?

To systematically address these inquiries, the authors initially conducted a theoretical study: synthesizing nearly 40 research works on the theme of CAS in the context of Mathematics Education. They categorized and analyzed these materials. Subsequently, an investigation was carried out, examining the current usage of CAS in teaching and learning Mathematics, involving three key groups: teachers, pre-service Mathematics teachers, and high school students. Drawing from the experiences with CAS, particularly the CAS service provided by the Wolfram Alpha website, the team proposed several scenarios for incorporating CAS into Mathematics Education.

Based on the authors' research approach, CAS, particularly Wolfram Alpha, with its significant technical and pedagogical potential, has remained largely underutilized in mathematics teaching at the general education level. However, it is believed that CAS can be effectively applied in line with the direction of the 2018 General Education Program in our country. Experiments have demonstrated that CAS is easily accessible to everyone and is suitable for a diverse range of teaching situations and content.

2. Content

2.1. CAS – The perfect combination of Mathematics and Computer Science

CAS constitute a system of tools that includes a set of algorithms to perform symbolic operations on algebraic objects, a language to implement these algorithms, and an environment to use that language. CAS typically encompasses a large algorithm library, efficient data structures, and support for complex computations with fast processing speeds.

Based on our research experience in the domain of computer algebra, involvement in developing several Maple modules, and reflections on mathematics teaching in general education schools, we propose the following process for the operation, development, and application of CAS:

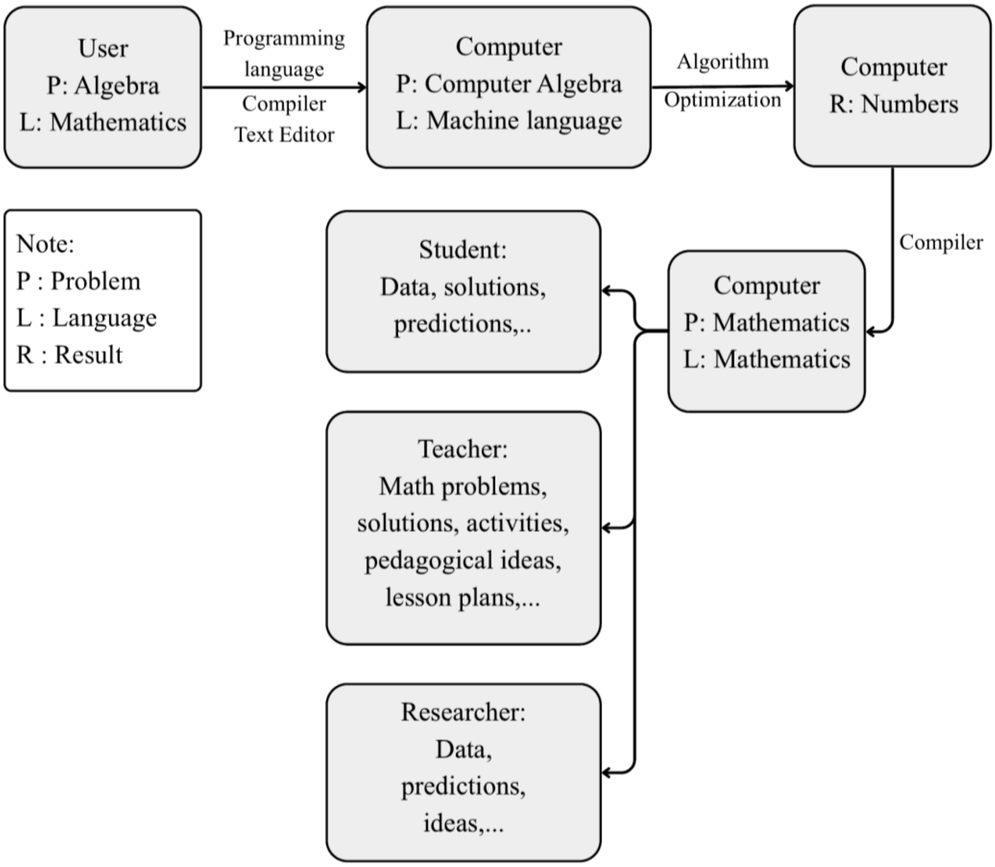

Figure 1. CAS operating diagram

The operational model of the Computer Algebra System (CAS) is illustrated in Figure 1, comprising three core components: P (Problem), L (Language), and R (Result). The user inputs an algebraic problem (P: Algebra) using mathematical language (L: Mathematics). Through the programming language, editor, and compiler specific to each CAS, the problem is processed internally and converted into machine language (L: Machine Language) for computation. The CAS then applies algorithms and optimization techniques to solve the problem and produce a numerical output (R: Numbers). This result is recompiled into mathematical language to serve various users.

According to a meta-study by Evans (2006) [13], CAS have been recognized as emerging since the 1970s, marked by the inception of REDUCE (1968) and MACSYMA (1970) as the pioneering systems widely employed. However, these initial systems operated exclusively on large computers. The advent of personal computers during this period led to the development of Algebraic Computing Programs tailored for smaller machines, such as muMath (1979), MAPLE (1985), Derive (1988), and Mathematica (1988), among others. Notably, MAPLE and Mathematica remain widely utilized to this day.

CAS found its application in university-level calculus courses from the early 1990s (Arnold, 2004 [14]; Nunes-Harwitt, 2004 [15]), facilitating algebraic operations and computations. Heid and Edwards (2001) [16] introduced four prominent pedagogical features that CAS can assume in Mathematics Education: (1) Using CAS to perform calculations to enable students to focus on concepts, (2) Utilizing CAS to generate numerous visual examples, (3) Employing CAS to find solutions for abstract problems, (4) Using CAS to create symbolic situations to assist students in concept formation.

Recently, several CAS have gained widespread usage, such as Wolfram Alpha, Microsoft Math Solver, Photomath, and MAPLE. These systems, accessible both online and offline, support users in streamlining problem-solving processes, graphing, experimentation, and mitigating simple errors through data input into the tool. Moreover, they can explain and guide users through various problem-solving methods across diverse mathematical topics, including algebra, geometry, calculus, trigonometry, and advanced mathematical content.

2.2. Literature reviews on the use of CAS in teaching mathematics

At the turn of the 21st century, during the synthesis of research findings in the field of Information and Communication Technology in Mathematics Education (ICT in Mathematics Education), Lagrange et al.'s meta-study in 2003 [17] scrutinized publications related to the utilization of information technology in Mathematics Education, noting that CAS constituted the most vibrant theme in two significant respects. Firstly, in terms of quantity, CAS comprised the most dynamic topic, accounting for approximately 27% of the total 662 publications from the most developed research areas. Secondly, CAS exhibited a high degree of diversity and richness in approach. These primary approaches encompassed five groups: tool description, description of creative activities in the classroom, assumption description about improvement, description of the effectiveness of CAS, and description of the conditions for CAS usage.

2.2.1. Opportunities and challenges of integrating CAS into teaching mathematics

Like any tool introduced into educational applications, CAS is subject to a dual consideration of advantages and disadvantages, opportunities and challenges, which the research community meticulously discusses.

**** Opportunities***

With the support of CAS, new opportunities have emerged for Mathematics Education, ushering in "the advent of a new dynamic classroom, in which teachers and students naturally become partners in developing mathematical ideas and solving mathematical problems" (NCTM, 1989) [18].

In Bawatneh, Zyad's study on the utilization of CAS in mathematics education (2012) [19], teachers and students employed CAS both technically and pedagogically. CAS was utilized for its technical functionalities, such as finding answers, as well as its pedagogical aspects, aiding in the exploration of mathematical concepts. The results noted time savings, as students could swiftly perform extensive calculations, such as determining the area of a region limited by two function graphs, solving equations, and systems of equations with accurate results. The use of CAS alleviated students' feelings of frustration when facing complex calculations. Observations indicated heightened awareness among students regarding problem-solving steps, and a reduction in minor computational errors typically encountered when students perform algebraic operations manually.

Pierce and Stacey (2010) [20] succinctly outlined the pedagogical opportunities offered by CAS as exemplary instances. Leveraging their computational power, CAS positively influenced both the curriculum and assessment in Mathematics Education. These systems effectively assisted students in efficiently completing "traditional" learning tasks while introducing engaging and effective "new" task formats. Consequently, the pedagogically effective learning environment in the classroom was enhanced, aligning positively with the practical and modern direction of teaching and learning for learners.

**** Challenges***

While the use of CAS in education is feasible and holds the potential to become a powerful tool for both teaching and learning Mathematics, the research on CAS utilization is still in its early stages globally. Numerous questions have been raised (Ball and Stacey, 2003 [21], Pierce and Stacey, 2002a [22], 2002b [23]): Does CAS influence students'' overall perception of Mathematics? Does CAS affect students' attitudes toward using technology in learning Mathematics? How can CAS be employed to enhance mathematical reasoning? What do students record? Regarding mathematical notations? How can we prompt students to think about Mathematics, not merely relying on technology? What changes can be expected in assessment and evaluation with the introduction of CAS?

2.2.2. Some points of consensus

Amidst the opportunities and challenges previously delineated, several perspectives in research on CAS in Mathematics Education have been put forth, which can be considered relatively consensual or minimally contentious, as follows:

- In the age of technology, it is necessary to "coexist" with CAS

In accordance with the Principles and Standards for School Mathematics (NCTM, 2000) [24], the "Principle of Technology" stands as one of the six principles aimed at promoting high-quality Mathematics Education. This principle explicitly states, "Technology is essential in teaching and learning Mathematics; it influences the Mathematics being taught and enhances students' learning capabilities.". Graphing calculators and CAS are considered by researchers as the most influential forms of technology, paving the way for fundamental changes in the methods of teaching Mathematics - an assertion drawn from the studies of Cooley, 1997; Dubinsky & Tall, 1991; Ellington, 2006; Gaulke, 1998; Habre & Grundmeier, 2007; Heid, 1988; Koh & Divaharan, 2011; and Porzio, 1995, as noted by Bawatneh, Zyad (2012) [19].

- The education program needs to be changed to adapt

How and why should the teaching content be modified? To craft a rational teaching program and leverage new opportunities, there are specific reasons for change (Stacey, 2003) [25]:

Three types of content benefit from the integration of CAS: Accessibility Enhancement, where certain content becomes more accessible, allowing new, challenging topics that are less approachable through traditional teaching methods to be taught with CAS support; Changes in Practical Value, as CAS transforms the practical value of content, altering the perceived usefulness of mathematical concepts; and Altered Perceptual Value, where CAS induces shifts in how content is perceived and understood.

CAS improves access to certain topics by removing technical barriers, enabling the inclusion of new content like matrix calculations in probability and extended graphing content in the new curriculum.

Time saved from manual calculations can be used to add content, deepen problem exploration, or apply knowledge. Students may choose between manual methods and CAS's technical features to solve problems.

- Teachers change their approach and education methods, including evaluation included

Accompanying the program changes, teachers must also adapt their teaching methods when engaging with CAS actively [25]. This involves designing a system of questions and tasks appropriate for when CAS is permitted for use in the classroom. This includes interspersing inquiries, note-taking, dialogue, and interaction during teaching hours to assess students' understanding of processes and problem-solving steps in Mathematics.

The assessment and evaluation content, along with the overall difficulty level of tests allowing CAS use, must undergo rigorous scrutiny. Clear and systematic guidelines should be provided to students regarding which intermediate answers should be presented. The questions posed should ensure no discrimination among various CAS tools. Simultaneously, with the support of CAS, there is an opportunity to pose newer questions to assess applied mathematical knowledge, utilizing CAS to aid in complex computational steps. Teachers, who are directly involved in the assessment process, need to continually update their knowledge of the new features of the CAS systems students use and adjust questions accordingly.

2.3. Researching and introducing some CAS

2.3.1. Criteria for evaluating and classifying CAS

Currently, numerous CAS have emerged with various features supporting the teaching and learning of Mathematics. To assess and categorize CAS, Santos (2022) [26] introduces several criteria, emphasizing capabilities and functionalities rather than aesthetic qualities. These criteria include five aspects: the ability to solve problems by subject; data input capabilities; instructional guidance capabilities; convenience; copyright - open-source and storage capabilities; along with other supplementary criteria.

Furthermore, not yet widely adopted, some CAS, beyond solving mathematical problems, also provide an additional digitized mathematical ecosystem that can assist learners in exploring ideas, principles, and other mathematical content. A comparison table of several popular CAS systems is presented by the authoring group in the attached *Appendix 1* (https://bit.ly/appendix1234).

2.3.2. The application potential of Wolfram Alpha in teaching mathematics

In the past decade, propelled by technological advancements, CAS has emerged with robust features, fostering the integration of CAS in education. Noteworthy among these algebraic computing systems, equipped with powerful functionalities and extensively researched for educational purposes, are Wolfram Alpha, MAPLE, Matlab, and others. Specifically, Wolfram Alpha stands out as a tool designed to generate answers to mathematical problems and provide additional information related to the given solutions.

Wolfram Alpha (available at: https://www.wolframalpha.com/), introduced in May 2009, is a web-based service developed by Wolfram Research utilizing Mathematica web technology. Leveraging its extensive knowledge base and sophisticated algorithms, Wolfram Alpha autonomously responds to queries, suggests algorithms, and efficiently handles complex mathematical operations in a brief timeframe.

The user submits a computational query, such as "derivative of x^4 + 9x^3 + 7x – 2". Wolfram Alpha responds with the derivative result: "Derivative: $\frac{d}{dx}(x^4 + 9x^3 + 7x - 2) = 4x^3 + 27x^2 + 7$", accompanied by a graph of the derivative function. Additionally, Wolfram Alpha provides supplementary information such as equivalent simplified forms, real and complex roots, as well as the domain, range, integral, and extrema of the derivative function. To support learning and analysis, the system allows users to expand the result by accessing the "Step-by-step solution" feature, which displays the solution process in sequential steps.

Dimiceli et al. (2010) [27], in responding to the question "Why Wolfram Alpha?" outlined several advantages of Wolfram Alpha, including:

- *Accessibility*: Users can access Wolfram Alpha anytime, anywhere, using their personal computers or mobile devices, reducing infrastructure pressure and facilitating online learning for students.

- *Reduced Syntax Complexity*: Wolfram Alpha significantly simplifies syntax, allowing users to employ natural language with Wolfram Alpha's syntax suggestions, saving time otherwise spent on parentheses or commas. This enables users to focus on the problem rather than syntax.

- *Comprehensive Information*: Wolfram Alpha provides more than a one-word (or number) answer to the initial question. Offering results in various formats from its extensive database is advantageous. Additionally, Wolfram Alpha displays the steps the system took to reach the solution, providing users with the opportunity to examine the process and explore new mathematical problem-solving methods.

- *Copy-Paste Ease*: Results from Wolfram Alpha can be easily copied and pasted into reports and presentations. The option of plain text copying from Wolfram Alpha's output allows for the reproduction of multi-step problem solutions and the presentation of various examples of the same concept without the need for retyping.

In general, Wolfram Alpha is more powerful than a graphing calculator; however, graphing tools excel in creating and zooming in on graphs. Rosly et al. (2020) [28] also argue that Wolfram Alpha is ideal for Math types that Google's calculator and most other computation websites cannot solve. Regarding the pedagogical potential of Wolfram Alpha in Math classes, Abramovich (2021) [29] noted results from teacher participation in experiments expressing a desire to use Wolfram Alpha in their classrooms. Using a tool like Wolfram Alpha, students can break down basic mathematical concepts and problems into smaller parts, representing them in various ways. Wolfram Alpha also serves as a tool for students to view solution steps for questions and problems. Teachers can utilize Wolfram Alpha as a guiding tool to help students understand concepts more deeply and distinguish between different concepts. This research also emphasizes that by employing technology to pose problems, teachers save time on instructional planning, allowing more focus on students' intellectual progress. Wolfram Alpha can support students in developing deductive reasoning skills and "applying their Mathematics to a wide variety of increasingly complex and novel problems".

2.3.3. Initial exploration of the Wolfram Alpha application landscape

To explore the knowledge, attitudes, and current state of CAS applications in general, and Wolfram Alpha in particular, in mathematics teaching and learning, we designed an online survey targeting three groups of participants: high school students, pre-service mathematics teachers (education majors), and in-service mathematics teachers. The survey had collected 168 responses, primarily from pre-service mathematics teachers (90 responses), followed by in-service teachers (29 responses) and students (49 responses). Separate questionnaires were designed for each group, but all followed a similar structure, consisting of the following sections: (1) General information about the respondents; (2) Awareness and usage of popular CAS tools (e.g., Wolfram Alpha, MAPLE, Photomath, Microsoft Math Solver); (3) Level of trust in or experience with CAS in solving specific types of problems (e.g., solving polynomial equations, computing derivatives and integrals, graphing functions); (4) Opinions on the role of CAS as a support tool in teaching or learning; (5) Views on whether students should be allowed to use CAS in math classes; (6) Frequency of CAS usage; (7) Perceived or experienced difficulties when integrating CAS into classroom practice.

The results show that among the listed CAS platforms, Wolfram Alpha, Photomath, and Mathway were the most widely recognized and used. Most respondents either believed or had already experienced that CAS tools could effectively support their work, such as solving computation-based exercises, preparing lesson plans, or verifying results. A notable portion of participants: 86.2% of teachers, 65.6% of pre-service Mathematics teachers, and 57.1% of students agreed that students should be allowed to use CAS tools under teacher supervision. However, the actual frequency of CAS use in teaching and learning remains limited: "never" among most teachers (9 out of 29), and "occasionally or very rarely" among pre-service teachers (32 out of 90) and students (15 out of 49). Commonly reported challenges include difficulty in assessing students' understanding, lack of classroom infrastructure, insufficient training and instructional resources, and limited class time. The survey results are updated in real time at the following link: https://bit.ly/kqkscas.

The survey findings reveal that although CAS or Wolfram Alpha possess the potential to support Mathematics teaching and learning, they have not been extensively utilized in educational activities. There exists a need to explore and employ these tools more effectively in instructional endeavors to ensure their appropriate integration.

2.3.4. The ability to support teachers and students

For teachers: Wolfram Alpha aids educators in various tasks, including solving computational exercises, lesson planning, composing mathematical problems, illustrating mathematical concepts, and generating problem-solving scenarios.

For students: Wolfram Alpha assists students in various aspects of the mathematical learning process, such as solving computational exercises, verifying solutions post-solving, testing hypotheses, exploring theorems and properties, aiding in deduction and proofs, self-learning, and exploring new knowledge... The potential of Wolfram Alpha in these tasks is illustrated through specific examples presented in *Appendices 2 and 3* (https://bit.ly/appendix1234) attached herewith by the authoring team.

2.3.5. Designing teaching scenarios involving Wolfram Alpha

To illustrate the feasibility and pedagogical intentions of our approach, we relied on the framework of the competency-based teaching outlined in Document 5512 to design several teaching scenarios. According to this framework, competency-oriented teaching sessions are typically structured into four (groups of) activities: motivation, new knowledge construction, consolidation, and application. Each phase is expected to address four key elements: learning objectives, content, expected student outcomes, and implementation strategies. However, within the scope of this article, we emphasize the implementation strategies, which follow the structure proposed by Nguyen Hung Chinh & Tran Cuong (2021) [30]. This structure comprises the following steps: (i) Teacher task handover; (ii) Student task execution - with necessary interventions by the teacher; (iii) Discussion; (iv) Conclusion.

Our primary approach can be outlined within a procedural framework:

Step 1. Content exploration: Strive to maximize Wolfram Alpha utilization in all lesson requirements (explicit or implicit) to establish a reservoir of potential activities with Wolfram;

Step 2. Commence lesson planning: Design/Select the regular lesson plan version (without Wolfram Alpha);

Step 3. Digitize the lesson plan: Mark and then choose components that can be "digitized with Wolfram Alpha";

Step 4. Refinement: Elaborate, review, test, and adjust comprehensively.

The author group devised a teaching scenario with Wolfram Alpha on the subject of "Newton's binomial theorem" (targeting 10th-grade students demonstrating strong academic performance, or those enrolled in advanced elective courses) for the new knowledge construction activity. With CAS support, teachers and students can explore mathematical concepts beyond the standard curriculum, such as the general form of the theorem. The content may be integrated into the official program or used as a thematic study. In this scenario, the teacher divided the class into pairs to perform the task as follows:

In 8th grade, when studying equations, we learned to expand:

$$(x+y)^2 = x^2 + 2xy + y^2;$$

$(x+y)^3 = x^3 + 3x^2y + 3xy^2 + y^3.$

Given the expanded triangle in the following form:

1 ______________ $(x+y)^0 = 1$

1 1 ______________ $(x+y)^1 = x+y$

... ... ______________ $(x+y)^2 =$ ....

... ... ______________ $(x+y)^3 =$ ....

... ... ______________ $(x+y)^4 =$ ....

... ... ______________ $(x+y)^5 =$ ....

... ... ______________ $(x+y)^6 =$ ....

a) Use Wolfram Alpha to complete the triangle above.

b) What comments do you have about the above triangle and the exponent rules for *x* and *y*?

c) Based on the discovered rules, predict the result of expanding $(x+y)^{12}$. Use Wolfram Alpha to verify the predicted result.

d) Use Wolfram Alpha to enter the command *choose(12,k)* with *k* ranging from *0 to 12* and compare the results with the coefficients of the terms in the expansion of $(x+y)^{12}$. In your opinion, what does "choose" imply here?

e) Write a general formula with arbitrary n.

Students utilized Wolfram Alpha to complete triangles and deduce certain observations about numerical triangles and exponential laws. Some conclusions drawn were: the number below equals the sum of the two numbers directly above it; the coefficients of the expansion exhibit symmetry and the exponents of *x* decreasing while those of *y* increase in order... Students recognize the relationship between expansion coefficients and combinations, leading to the formulation of the generalized Newton binomial theorem. A comprehensive description of the activity is provided in *Appendix 4* (https://bit.ly/appendix1234).

3. Conclusions

The study of CAS in teaching Mathematics ~~Education~~ has long been a topic of international interest, with a plethora of works and research outcomes ensuring a solid scientific foundation for integrating CAS into educational practice.

Aligned with the objectives of the 2018 General Education Program aimed at fostering student competencies, the integration of information technology during teaching hours stands as a necessary and effective approach in teaching mathematics ~~Education~~. Among these systems, CAS, specifically exemplified by Wolfram Alpha, emerges as a powerful tool that supports teachers in constructing and executing teaching plans.

The 2018 General Education Program encompasses numerous content elements that are highly conducive to the integration of CAS into teaching. CAS aligns well with the suggested lesson design model outlined in Document 5512, promoting an enhanced focus on experiential learning-based mathematical education and other contemporary teaching trends to develop students' mathematical competencies.

A wide range of Computer Algebra System (CAS) tools can be implemented in teaching mathematics. Among them, Wolfram Alpha stands out as a highly accessible tool with substantial pedagogical potential. When employed within a guided discovery framework, Wolfram Alpha can effectively support instruction across the four archetypal scenarios in teaching mathematics: teaching concepts, theorems, rules/methods, and problem solving. These pedagogical affordances have been further illustrated through specific examples in a report submitted to the Scientific Conference of the Faculty of Mathematics and Informatics, Hanoi National University of Education, in May 2023. The full text of this report is available at https://byvn.net/Fpmc.

Subsequent research avenues might involve experimental validation of the proposed strategies' effectiveness and their implementation in actual teaching practices. Additionally, exploring the applied research aspects of CAS systems beyond Wolfram Alpha within Mathematics Education could culminate in the creation of reference resources aiding educators in designing teaching activities.

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