A Proposed TPACK Model of Teaching STEM with AI Components: Evaluating a Teacher Development Course for Fostering Digital Creativity

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Abstract: In this study, a novel design of STEM activities was proposed with a focus on concepts of Internet of Things (IoT) and artificial intelligence (AI) components for developing the problem-solving abilities and digital creativity of in-service primary teachers. This study evaluated the effectiveness of a 6-hour course for developing primary school teachers' competency in teaching AI-integrated STEM activities and developing their digital creativity. One hundred and ninety-one teachers from 108 primary schools attended the development course and completed survey and creativity evaluation. Teachers' responses to surveys on the TPACK model and digital creativity evaluation sheets were collected. The paired t-test results indicated statistically significant improvement on all 17 TPACK items with a large effect size (Cohen's d = 1.213). For the digital creativity evaluation completed, 81.15% of the teachers demonstrated digital creativity and expressed their ideas in designing IoT systems and many of the designs included AI components. The paper concluded the implications of this study and future work were discussed.

1 INTRODUCTION

Artificial intelligence (AI) technology has become more prevalent in daily life in the digital era (Kong et al., 2021). To ensure that teaching and learning content is meaningful and appropriate, we suggest integrating the essential AI experiences, such as the interaction with and training of AI models, into STEM activities. Integrating AI models in STEM systems makes them richer and more human-friendly (Ouyang et al., 2023). Another objective of promoting STEM education with AI components is to strengthen students' problem-solving abilities and inspire their digital creativity. Incorporating AI components in STEM activities provides opportunities for students to cooperate with peers in the problem-solving processes when designing systems with appropriate AI algorithm and training models (Lin et al., 2021). Furthermore, these integrated activities provide opportunities for students to be inspired with digital creativity because they can transfer what they have learnt to new scenarios.

We select the internet of things (IoT) as the source of the key concepts in the design of our STEM activities because IoT is assumed to be permeate every part of daily life and become omnipresent in the physical world in the digital era (Sedrati et al., 2022). In this study, we try to develop teachers' understanding of the latest development through building physical artefacts using IoT and AI concepts in STEM activities of our professional development course, ultimately enabling them to promote AI and STEM Education in their schools. Although there are researchers working with the development of students' AI Literacy (Touretzky et al., 2019), there is a lack of research on integrating AI and IoT concepts with STEM activities. We propose a novel approach to include AI and IoT concepts in STEM activities of primary schools. However, as most of the in-service teachers have limited STEM-related

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technological knowledge and lack confidence in teaching STEM activities in this context, there is a need for teacher development (Cavlazoglu & Stuessy, 2017; Schreiter et al., 2023). The specific research questions addressed were as follows:

(1) What effects does the teacher development course have on teachers' competence in teaching STEM with AI components?

(2) How do teachers who have participated in the teacher development course developed their digital creativity?

2 LITERATURE REVIEW

2.1 Internet of Things Concepts, Problem-Solving Abilities, and Digital Creativity

The major focus of our STEM activities is to promote IoT concepts, problem-solving abilities, and digital creativity. Students are guided to create IoT systems using microprocessor and block-based programming on AI-enabled platforms connected with the microprocessor. Playing with and building a functional system is helpful for students to understand how an IoT system works. When Ashton (2009) first introduced IoT, he proposed that computers can observe and understand the world using sensor technology without any help from humans. The functionality of IoT is delivered by six elements: object identification, sensing, communication, computation, services, and semantics (Al-Fuqaha et al., 2015). Object identification and semantics are important elements of IoT. It would be too complicated for primary students if we include all six elements. We adopt a simplified IoT concepts of sensing, reasoning, and reacting, which are the essential elements of automation systems, for designing our STEM activities in the primary school context. Sensing refers to the use of sensors or a microprocessor with sensors to detect and transfer data. Reasoning refers to the use of a microprocessor and programming codes that process the data with computation and determine the reactions of a system. Reacting refers to the final reaction of a system to provide services after communication among the devices involved. The implementation of sensing, reasoning, and reacting in IoT systems can support automation and interaction with humans based on programming codes and communication between devices.

STEM education aims to develop students' problem-solving abilities. Sullivan and Heffernan (2016) proposed that STEM activities work to develop four aspects of problem-solving abilities: casual reasoning, sequencing, conditional reasoning, and engineering systems thinking. Kong (2023) proposed a pedagogical design which focuses on developing students' problem-solving skills in four aspects within cross-disciplinary STEM activities. Causal reasoning refers to the identification of casualty, which is the relationship between the causes and effects of an incident (Van Vo & Csapó, 2023). Students can exercise this skill by investigating the cause of system failure and fixing bugs. Sequencing is defined as "the ability to put items in a specific order" (Sullivan & Heffernan, 2016, p. 8). As students learn basic programming knowledge during the activities, they develop sequencing skills by arranging the programming blocks into a specific order with the aim of automating the system. Conditional reasoning is the process involved with statements of the form "if A then B," in which A is the antecedent and B is the consequent (Nickerson, 2015). Conditional reasoning also refers to logical reasoning, which is important in the process of building an automated system (Sullivan & Heffernan, 2016). Engineering systems thinking is "the ability to understand the whole system or perceive how the components (i.e., person, part) function as part of a system" (Frank, 2002, p. 1351). In STEM activities, it is crucial for students to understand the function of each component and how they interact in the whole system.

Despite the fact that recent studies have highlighted the significance of digital creativity and the necessity for students to evolve from mere consumers to innovative problem-solvers in the digital age (Kong & Lai, 2021), there is a noticeable gap in understanding the extent to which students are able to transfer the skills and knowledge acquired from STEM-based educational activities to practical, real-world scenarios. This research would provide valuable insights into educational strategies that can better prepare students to contribute innovatively and adaptively to the rapidly evolving society.

2.2 Integrating STEM with AI Components

As technology advances rapidly, new concepts can be added to STEM activities to motivate students in learning actively. Promoting AI literacy is one of the new learning objectives of our proposed STEM activities. AI literacy can be defined as the "understanding of AI concepts and competencies in using AI concepts for evaluation and using AI concepts for understanding the real world" (Kong & Zhang, 2021, p. 12). To help students to develop AI literacy, we introduce the five big ideas in AI: perception, representation and reasoning, learning, natural interaction, and societal impact (Touretzky et al., 2019). These five big ideas are used to develop students' basic understanding of AI. Among the five big ideas, we emphasise giving primary students experience in interacting with AI and, through hands-on activities, develop the concept of how machines "learn", which is a key concept of AI at present. Students are guided to figure out how computers learn from data as they take part in the data training process. We also inspire primary students to apply what they have learnt from the AI examples by figuring out potential uses in real-life situations. This can help to develop their digital creativity and give them a better understanding of the societal impact of AI.

AI can help promote IoT concepts and provide flexibility in building STEM systems. One of the learning objectives of our proposed STEM activities is to promote IoT concepts. Students usually use sensors, microprocessors, and actuators to automate systems in STEM activities. AI can help to promote IoT concepts and facilitate more interactions between humans and the system (Ghosh et al., 2018). AI and IoT can be integrated to develop intelligent applications that can benefit users (Katare et al., 2018). Such an integration of AI and IoT is known as the artificial intelligence of things (AIoT), which makes applications "smarter" by giving them the ability to collect and process data (Qiu et al., 2023). The machine learning process allows the system to learn complicated human behaviours and react accordingly.

2.3 Pedagogy of "to Play, to Inquire, to Assemble, to Code, to Reflect, to Create"

Based on Kong and Lai's (2021) pedagogy of "to play, to think, to code, to reflect" for teaching computational thinking through programming to enable students understand how the programs work, plan before coding, learn problem-solving skills in the coding process and finally students are guided to reflect on what they have learnt and think about the possible use of what they have learnt in other occasions. This pedagogy aims at developing problem-solving skills and digital creativity of students.

In this study, we proposed a pedagogy of "to play," "to inquire," "to assemble," "to code," "to reflect," and "to create". This pedagogy provides students with an introduction to playing around with a STEM system. The objective of the playing activities is to arouse their interest in STEM, which is important in the primary school context. This can trigger students' interest in inquiring how the STEM system works. Students will then disassemble the STEM system and understand how each component—digital and non-digital—works and then reassemble the components into a working system, following some coding and data training activities if AI models are involved. Students will be asked to reflect on what they have learnt in building the STEM system and to propose and discuss other possible STEM systems using similar technologies to those in the example system. Pedagogy of "to play" and "to inquire" at the beginning of each STEM activity lays a good foundation for students to proceed with the STEM activities of "to assemble," and "to code" which involve building STEM artefacts, thus helping students to develop their problem-solving abilities.

2.4 TPACK Framework in Guiding and Evaluating Teacher Development

The Hong Kong Education Bureau (2015) has highlighted the importance of providing teacher development in promoting STEM education. Indeed, there is a genuine need for teacher development courses to support teachers to teach STEM to develop students' problem-solving abilities and digital creativity. In this study, we use the TPACK framework to guide the design of a teacher development course in teaching STEM activities with AI components (Mishra & Koehler, 2006). TPACK framework includes seven components, including three major domains of content knowledge (CK), pedagogical knowledge (PK) and technological knowledge (TK), and their interactions which forms technological content knowledge (TCK), technological pedagogical knowledge (TPK), pedagogical content knowledge (PCK) and technological pedagogical content knowledge (TPACK).

In our context, CK refers to the IoT and AI concepts involved in STEM activities and the problem-solving skills involved in building the STEM system; TK refers to the general knowledge in using technology including computer, coding platforms, microprocessors and different electronic components; PK refers to the general pedagogical knowledge in teaching STEM activities, such as to guide students to use discussion and/or group activities to accomplish the problem-solving process and to generate ideas for digital creativity. More importantly, teachers need to guide students to learn from "to play" and "to inquire" so that students know why and how to complete the "to assemble" and "to code" process and finally learn from reflection on problem-solving and become more creative. TCK refers to the understanding of the technological functions of each digital and non-digital component used for building the STEM system; TPK refers to the use of technology and pedagogy in general for teaching outside our scope of STEM; PCK involves the pedagogical design for achieving the learning objectives of our STEM activities; TPACK refers to the synthetisation of knowledge in our learning context of teaching STEM with AI components.

3 METHODOLOGY

3.1 Participants and Procedure

Two hundred and one teachers from 108 primary schools attended the 6-hour teacher development course. The course introduces our method of teaching STEM with AI components in primary schools. Data included pre- and post-surveys on TPACK and digital creativity designs. A total of 192 responses were collected from pre- and post-surveys. A total of 191 teachers expressed their digital creativity ideas in writing and sketches after the course.

3.2 Instruments

Surveys on TPACK: The instrument consists of 17 items. A 5-point Likert scale from 1 (strongly disagree) to 5 (strongly agree) was used to score each item. Cronbach's alpha for the pre- and post-course survey was above 0.85. Sample items are as shown below: TCK—I understand the functions that sensor, microprocessor and actuator perform in the IoT systems; TPACK—I can teach STEM lessons that appropriately combine the content of STEM, technological innovation, and proper teaching approaches.

Digital creativity evaluation sheets: After the course, we also asked the primary school teachers to suggest new STEM applications other than those they had learnt in the course. These design suggestions were used to have a brief understanding on the digital creativity development of these teachers. Criteria of the creative ideas are listed in Table 1.

Table 1: Marking criteria of creative ideas.

Criteria	Mark
Ideas that were identical to the applications discussed in the course	0
Description of the application could be clearer	1
New application designs that used the IoT concepts of sensing-reasoning-reacting	2

3.3 The Teacher Development Course

The course was made up of three teaching units. The first unit was about the design of a maze game, in which a character on a monitor is controlled by a hand-made physical joystick connected to an internal microprocessor. In playing with the system, the teachers gain an initial understanding of the core IoT concepts of sensing-reasoning-reacting. The second unit is a table tennis game that includes IoT concepts and AI concepts. To complete the system, teachers are required to train AI models with machine learning by striking different poses in front of webcams. Trained AI models are then extracted and installed in the game system, which reacts to poses and motion sensed by an accelerometer in the hand-made physical racket. The third unit is a Chinese face-changing performance game, which again involves IoT concepts and AI concepts. Teachers can perform a face-changing show using the system. Teachers are required to train AI models for recognising facial expressions. The models are then extracted for use in the performance game application. By developing these AI models and engaging in further discussion, teachers develop basic AI concepts and learn how to use them in building STEM systems with AI components.

In the introduction to each unit in the development course, the teachers were briefed on the technologies involved in the unit and the content knowledge to be involved (TK, CK, TCK). They were then encouraged to go through the teaching process of "to play" "to inquire," "to assemble," "to code," "to reflect," and "to create" in each teaching unit to give them experience of the teaching process and the methods for developing problem-solving skills and inducing digital creativity (PK, PCK, TPK and TPACK).

Taking Teaching the Smart Ping Pong Course Unit as an example, the teachers were briefly introduced to the technology components involved with the application before they began to play with it. They then experienced the pedagogical processes with the STEM systems, from "to play" through to "to create". Towards the end of this teaching session, the teachers were guided to reflect on the IoT and AI concepts they had learnt and the pedagogical practices for teaching the unit. The teachers were finally asked to share ideas with their learning peers for making new systems by applying what they had learnt in the teaching unit, including the technology components and the experience of training and using AI models in the STEM system. This was an important session to develop digital creativity in the teacher participants and to give them knowledge on how to inspire digital creativity in their students when they return to their school to teach. Smart Ping Pong, a table tennis gaming system, is used here to illustrate the pedagogy. An AI model is trained, extracted, and stored in the Smart Ping Pong application. Webcams connected to the computer continuously capture images of players and send them to the computers. The computers use the trained AI models to reason and categorise these images into "left" and "right" strokes in the table tennis game and then react to the strokes of the players in the computer monitor. Figure 1 shows an illustration of delivering the IoT concepts of sensing-reasoning-reacting with AI components in the Smart Ping Pong system.

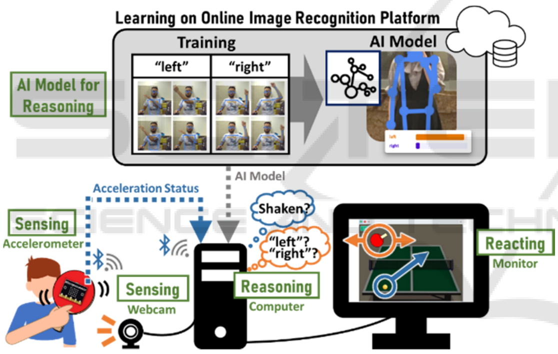

Figure 1: The IoT concepts of sensing-reasoning-reacting with AI components in the Smart Ping Pong system.

The built-in accelerometer of the microprocessor installed in the physical racket held by the player continuously senses the acceleration status and transmits the status data to the computer using Bluetooth. To interact with the system, teachers held the physical rackets and performed "left" and "right" strokes in front of the webcams, in reacting to the strokes of the virtual players on computer monitors. Teacher participants learnt about the AI concept of confidence level, and understand that decisions made were not always accurate.

After playing with the system, the teacher participants were asked to move on to the "to inquire" process. The teachers were asked to consider how the system in Figure 2 works as a whole by sensing, reasoning, and reacting with parts. The parts include the physical racket containing a microprocessor with accelerometer, battery box for the microprocessor, webcam, computer, and computer monitor. The teachers developed engineering systems thinking in putting all these parts together to work as a system. Before moving on to the "to assemble" and "to code" elements, the teachers were introduced to the process of teaching the machine to learn to categorise the strokes in the table tennis game as left and right strokes. The AI model was therefore trained to learn the left and right strokes by collecting these images and assigning them labels of "left" and "right". In the process of training these AI models, teachers learnt about the five big ideas of AI. After exporting the model to the Smart Ping Pong application, the teachers coded for the responses to the two conditions after the AI model recognises the poses of the players. The virtual racket on the monitor moves to the right on the monitor when the "left" pose is recognised and to the left when the "right" pose is recognised (see Figure 2).

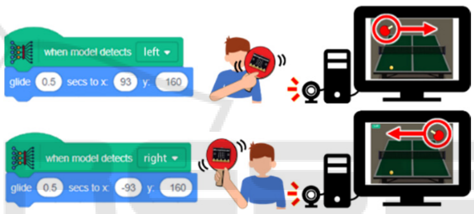

Figure 2: Teachers practise conditional reasoning with coding for movement of the virtual racket in the opposite direction indicated by the AI recognition results.

In the "to assemble" and "to code" elements, the teachers were asked to build the system by assembling the physical part and coding on block-based programming environment in driving the system to work together. In the process of building the system, the teachers exercised four aspects of problem-solving skills. Figure 3 shows one of the STEM activities in constructing the physical racket step-by-step with a cardboard tube, battery box, microprocessor, cardboard base and cover.

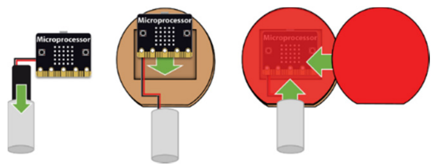

Figure 3: Teachers practise sequencing by constructing the physical racket step-by-step with a cardboard tube, battery box, microprocessor, cardboard base, and cardboard cover.

After a whole system is assembled with parts, it might not function as expected. In the "to assemble" activity, the teachers exercise causal reasoning to find out the source of errors and rectify them. Figure 4 shows some possible sources of malfunction. For example, a malfunction could be caused by the electricity supply failure of the microprocessor (Figure 4a), low-quality photos causing AI pose-recognition failure in deploying the AI model (Figure 4b), and/or losing the Bluetooth connection between the computer and microprocessor (Figure 4c).

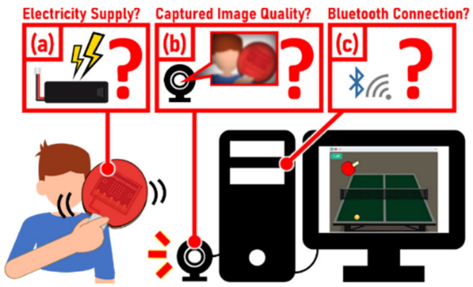

Figure 4: Teachers practise causal reasoning while assembling the Smart Ping Pong system.

In the “to create” activity, the teachers were given time to discuss and develop new ideas for solving real-world problems by introducing other AI models using sensors and actuators that might interest them and putting them together with the microprocessor and computer that they had just experienced. The brainstorming process already helped them to apply what they had learnt in these lessons.

In the “to reflect” session at the end of each lesson, the teachers were asked to reflect on what they had learnt and how to improve the pedagogy of teaching the unit, with an emphasis on the development of problem-solving abilities and inspiring digital creativity. The teachers were also guided to reflect on their experiences in building the system and to understand that dealing with failures in the process of building these systems is part of the learning process in STEM activities.

4 RESULTS AND DISCUSSIONS

4.1 Teachers’ TPACK Development

A paired *t*-test was carried out to calculate the significance of changes in teachers’ TPACK after completing the teacher development course. The results show significant improvement on all items with a medium to large effect size. A significant improvement was found in overall result [*t*(190) =16.770, *p* < .001]. For Cohen’s d, a value of 0.2 indicates a small effect, 0.5 a medium effect, and 0.8 a large effect. The overall result indicated a significant improvement with a large effect (Cohen’s d = 1.213). A significant improvement was found in all TPACK items, with a large effect size on CK [*t*(190) = 18.539, *p* < .001] (Cohen’s d = 1.341), PK [*t*(190) = 11.616, *p* < .001] (Cohen’s d = 0.841), TCK [*t*(190) = 15.346, *p* < .001] (Cohen’s d = 1.110), TPK [*t*(190) = 14.299, *p* < .001] (Cohen’s d = 1.035) and TPACK [*t*(190) = 13.604, *p* < .001] (Cohen’s d = 0.984), and a medium effect size on TK [*t*(190) = 9.967, *p* < .001] (Cohen’s d = 0.721) and PCK [*t*(190) = 10.398, p < .001] (Cohen’s d = 0.752). Descriptive data is shown in Table 1. The paired *t*-test result suggested that the teacher development course greatly improved the teachers’ confidence in teaching IoT concepts and problem-solving abilities and inspiring digital creativity (CK) with the use of proper technology tools (TCK). The paired *t*-test result also suggested that the teacher development course has greatly improved the teachers’ confidence in the use of general pedagogical knowledge (PK), such as collaborative learning in teaching STEM activities, technological pedagogical knowledge (TPK), which is the use of proper pedagogy in delivering technological knowledge to students, and technological pedagogical content knowledge (TPACK), which is the teaching of STEM activities in the specific context of STEM lessons. The result also suggested that there is improvement on teacher’s confidence in general technological knowledge (TK) and the use of content knowledge in handling the learning difficulties of students (PCK) after attending the course.

Table 2: Paired t-test results of the TPACK Survey.

	Pre		Post		
	Mean	SD	Mean	SD	*t*-value
CK	3.02	0.91	4.05	0.60	18.539***
TK	3.47	0.84	3.99	0.69	9.967***
PK	3.34	0.70	3.89	0.67	11.616***
PCK	3.35	0.78	3.91	0.72	10.398***
TCK	3.11	0.89	3.98	0.66	15.346***
TPK	3.07	0.91	3.94	0.71	14.299***
TPACK	3.16	0.83	3.91	0.69	13.604***
Overall	3.21	0.74	3.96	0.62	16.770***

4.2 Evaluation of the Digital Creativity Development of the Teacher Participants

Two members of the research team were assigned to mark the teachers’ designs independently. The inter-rater reliability was ICC = 0.844 (p < .001) with 95% confidence intervals ranging from 0.797 to 0.880, indicating substantial agreement between the two raters. Among the 191 teachers who completed the surveys, 60 (31.41%) were given 2 marks, 95 (49.74%) were given 1 mark, 26 (13.61%) were given a 0 mark for their answers, and 10 (5.24%) did not respond to the question. To summarise, 155 (81.15%) of the teachers showed their digital creativity in designing IoT or AIoT systems after attending the development course. Figure 5 shows one such design by a teacher participant, which is for a system to help students to learn action verbs. The teacher participant proposed the use of a video camera to sense students' postures. The application would pick an action verb from its vocabulary at random and show it on the computer monitor. The students would be required to act out their understanding of the action verb, and a trained pose-recognition AI model would judge whether the action was correct. For example, if the computer screen displayed "jump" on the monitor, and a jumping posture was captured by the video camera and recognised by the pose-recognition AI model, "correct" would be shown on the computer monitor.

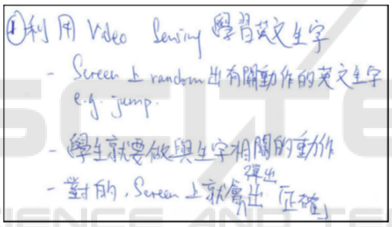

Figure 5: Teacher's design for a system on learning English action verb vocabulary.

Overall, the design examples demonstrate that teachers were able to design IoT systems and were very often able to enrich their designs by integrating AI perception models for recognising images, poses, hands, bodies, faces, facial expressions, and sound.

5 CONCLUSION AND FUTURE WORK

The results of this study suggest that the teacher development course is helpful in developing teachers' competency in teaching AI-integrated STEM activities and developing their digital creativity. With the result of the paired *t*-test analysis of the pre-course and post-course of TPACK survey completed by 191 participants, the course was found to be significantly helpful in improving teachers' confidence in all TPACK dimensions, including TK, PK, CK, TCK, TPK, PCK, TPACK. The results of the survey and the teacher participants' design artefacts show the growth of CK and TCK among the teachers, including IoT concepts, AI concepts, and problem-solving skills. This growth is helpful for teachers in teaching and supporting STEM activities with AI components in their schools, and in developing the related concepts and problem-solving abilities in their students in this context. The teachers were also inspired by the pedagogy of "to play," "to inquire," "to assemble," "to code," "to reflect," and "to create" to deliver STEM activities for teaching IoT and AI concepts and were exposed to ways to develop problem-solving abilities and foster digital creativity in learners.

Two limitations of this study are identified. First, without data from primary students whose teachers participated in the development courses, it remains unclear if the observed improvements in teachers' competency in teaching STEM activities with AI components effectively enhance students' understanding of related concepts, problem-solving skills, and digital creativity. Second, the confidence and capabilities of teachers in teaching STEM with AI components may fluctuate after they apply this teaching in real-world classrooms. In this respect, this study suggests two directions for future investigations. First, there is a need to analyse primary students' progression in IoT and AI concepts and their views of their problem-solving abilities and digital creativity development after participating in STEM activities in their schools. A multi-level analysis can then be conducted on the effect of the development course on teachers and whether this effect cascades to the achievement of students taught by these teachers. Second, it would be interesting to further investigate the teachers' views of their teaching competency after they teach their students in STEM classrooms, and especially to compare their responses with those collected from the post-course survey.

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