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Bridging the Gap in STEM Education by Visualizing Physics Concepts with 3D Printing

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ABSTRACT

STEM (science, technology, engineering, and mathematics) is often perceived by students as a difficult area of study, which can lead to many learning challenges. As today's world technology becomes part of everyday life, students who avoid STEM are more likely to lack the skills and understanding needed to deal with real-world problems. Meanwhile, as part of STEM, Physics, a branch of science that explores matter, energy, and fundamental force in which this fundamental are often difficult to visualize and understand by many students. The struggling faced by them then diminishes their interest in learning science. Therefore, to help students understand and stay engaged in Physics, 3D printing technology was used to create clear and tangible learning materials. 3D printed kits were developed according to the challenging topics in physics and accompanied with a teaching module. This study introduces the Kinetic Vision module, which integrates 3D-printed learning kits with game-based activities to support more engaging and meaningful physics learning. Two interactive kits which were Galaxy Exploration and Physics Wordhunt. were designed and implemented with primary school students to facilitate experiential and kinaesthetic learning. The feedback from the preliminary implementation were analysed and the data from the preliminary implementation showed a strong positive response to the use of the 3D printed tools. Particularly all participants reported that activities designed in the module as enjoyable and they would like to participate in the similar future activates. This findings suggesting a strong alternative for the module to be used further. Besides, the participants also described that the Physics kit using 3D models encouraged and helped them to improve their understanding especially in the topics of Gravitation and Solar System. The tactile planet models were regarded as the most useful component of the learning experience. In addition, the participants reported noticeable

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improvements in teamwork and leadership, however varied outcomes in critical thinking was observed. Therefore, the results highlight how 3D printed kits possible to enhance physics education by helping students grasp complex concepts more effectively while also encouraging collaboration and active participation. Hence, this study demonstrates the value of student-centered, creative approaches in STEM learning.

1. Introduction

The rapid growing in the development of science and technology integrated with the rapid progress of Industrial Revolution 4.0 (IR4.0) makes Science, Technology, Engineering and Mathematics (STEM) education become more significant as a career element in the future [12,28]. However, in Malaysia, participation in STEM education is still below than expected, and this become major challenge to achieve to goals of 60 percent choose STEM field [13,21,23] Meanwhile, the estimated required registered scientist and engineers in Malaysia would be at least 500,000 to meet the demands of Industry 4.0 by 2020 which reported by National Council for Scientific and Research Development [17]. In addition, the Ministry of Science, Technology and Innovation (MOSTI) plays a central role in Malaysia's aim to become a high-skilled nation through the National Science, Technology, and Innovation Policy. The policy is built on key pillars, including the development of adaptive Science, Technology and Innovation (STI) talent, stronger STEM education, broader participation in STI fields, and increased demand for skilled professionals. These priorities especially important as technology continues to evolve quickly and the global economy changes, since both factors strongly influence industrial development and long-term economic stability [20,26].

In addition, the relevance of science and technology among students has been highlighted in the Agenda 2030 which encompasses sustainable development goals (SDGs). This SDGs which seeks to strengthen the social, economic and environmental development. Achieving the goals of Agenda 2030 depends on science and logical thinking that are applied in a holistic and integrated way across global, regional, national, social, and individual contexts. Meanwhile, the talents in technology are considered high-skilled talents and are the backbone of all economies [25, 26]. However, the largest challenge that our government is now facing is the initiative to boost STEM [33]. This crucial problem needs to be tackled immediately or it will have a major impact on the nation's innovation and development strategy which depends on at least 500,000 workers in the science stream for the foundation of our country. Additionally, it may hinder Malaysia's ambition to develop into a persuasive country (Agommuoh, and Ifeanacho, 2012; Idris and Nachiappan, 2023). Continued support is outlined in the Malaysian Education Blueprint 2013–2025, which aims to equip students with the knowledge and skills required to meet with the increasing demands of a modern and industrial economy [9,20].

The decreasing interest of school students in STEM has become a growing concern for both stakeholders and the nation, highlighting the immediate action to address the problem [9,23]. A study in 2022 uncovered notable variations in student engagement with STEM subjects, reaching its high point at 48.15% in 2012 and experiencing a decline to 40.95% in 2021. Besides, another study investigated the factors that influence students' interest in STEM and findings showed that the pedagogical approaches used by educators had the greatest impact on this phenomenon due to the inadequate pedagogical design and delivery. It then followed by the challenging content of the subject [1,13,18,33]. Meanwhile, the teacher-centred teaching style also led to a lack of interest among students as learners were not actively involved in the lessons [20]. Therefore, immediate action is required to develop new teaching strategies and strengthen educators' effectiveness in

delivering knowledge. Peer-to-peer interaction has been identified by an education leader as a successful strategy for enhancing secondary students' comprehension of STEM concepts.

Meanwhile, designing learning approaches to meet students' individual needs can improve their interest in STEM subjects. At the same time, students need to actively engage with the material to align with their teachers' instructional methods. This combination encourages a lively and rewarding learning experience for both students and educators [2]. As STEM concepts are often complex and abstract concept, making it difficult for some students to visualize them, which can weaken their interest [12,23]. Moreover, high-achieving students benefit from effective teaching strategies that help them deepen and expand their knowledge [12,20,23,25].

As an alternative, integrating 3D printing technology into STEM subjects provides an innovative way to enhance both teaching and learning experiences. This approach can capture students' attention, boost motivation, and improve their understanding of complex concepts. Using 3D-printed kits, students are encouraged to explore, analyze, and evaluate different ideas related to the subject, fostering critical thinking and ultimately supporting better academic performance. One effective strategy for introducing 3D printing in secondary school STEM education is through a conceptual framework that emphasizes learning by design, allowing students to actively engage in the creation process. This method promotes hands-on, student-centered learning and deeper knowledge acquisition [4,16, 19,24].

In this study, gifted students actively lead the process, using their advanced Physics knowledge to develop 3D-printed educational modules with support from their educator. The use of interactive 3D-printed kits, referred to as *Kinetic Vision*, is intended to increase students' interest in STEM and support multisensory and inquiry-based learning at both primary and secondary levels. This project aims to design an educational board-game-based kit, evaluate its effectiveness in improving students' understanding of Physics concepts, and develop a sustainable learning tool that creates a more engaging classroom environment. The conceptual framework of this study is presented in **Fig. 1**.

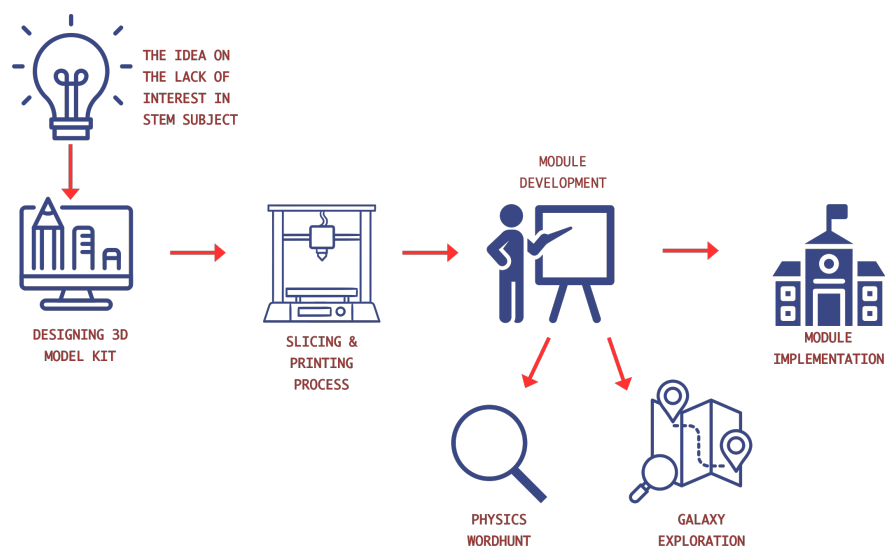


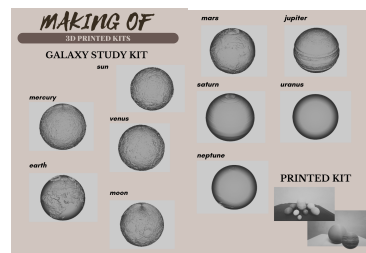
Fig. 1. Conceptual framework of kinetics vision module

2. Methodology and Data Collection

2.1 3D Printed kits development

In this study, physics as part of STEM subjects was focused specifically in Gravitation and Solar System. The development of 3D printed kits model was developed according to the topic focused. Briefly, digital modeling was employed to create 3D-printed models tailored for the kinetics vision

kits model by using computer-aided design (CAD) software, specifically TinkerCAD and open source [3]. There were two types of kits in Kinetic Vision were developed named as *Galaxy Exploration* (Fig.2a) and *Physics Wordhunt* (Fig. 2b).



(a)

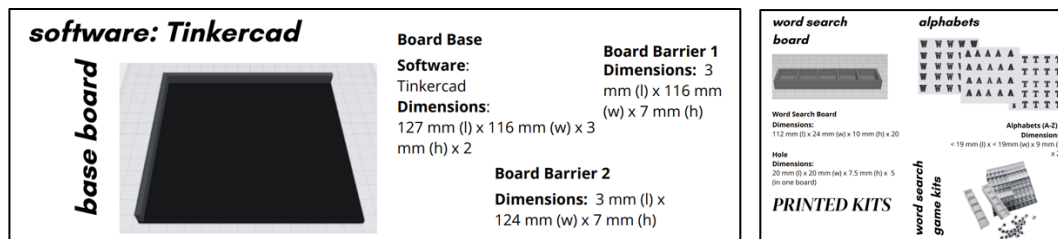


Fig. 2 The making of 3D model of (a) Galaxy exploration and (b) Physics wordhunt using tinkercAD software

The 3D models for each object were exported in the standard triangle language (STL) file format. Subsequently, these files were sliced into multiple cross-sections and sent to the 3D printer. As a result, the files undergo a slicing process using Creality-slicer 4.8.2 software to generate a G-code file. This G-code file is derived from the STL model, which is sliced into cross-sections to form toolpaths. Subsequently, the G-code file is interpreted by the printer, instructing the extrusion of materials and movement of the print head to fabricate the intended model using a 3D printer, specifically the Sermon Creality V1 Pro 3D printer. During the material extrusion phase, a heated extrusion nozzle melts the plastic material using polylactic acid (PLA) filament acting as ink [22]. Once melted, the material is extruded through the nozzle and then cooled to solidify, shaping the final geometry of the desired model [6,30]. The process flow is illustrated in Fig. 3.

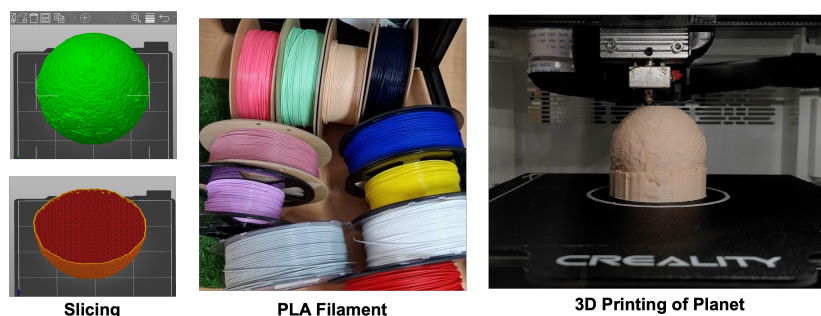


Fig. 3. (a) 3D printing and (b) 3D printed of *Galaxy Exploration* and *Physics Wordhunt*

1.2 Development of 3D Kinetics Vision Module

A STEM-focused Physics teaching module was created to boost student engagement through hands-on, interactive learning. The module includes two main activities: *Galaxy Exploration* and *Physics Wordhunt*, both supported by specially designed game cards. For *Galaxy Exploration*, the cards feature factual questions about planets, aimed at helping primary school students learn about

the solar system. In contrast, the Gravitation game cards are designed for secondary school students to reinforce their understanding of gravitational concepts within the Physics curriculum.

The developed module provides detailed instructions for creating and using 3D-printed instructional kits, along with structured activity plans and worksheets tailored to each activity. These kits, together with the custom game cards, were designed to support hands-on, experiential learning and to evaluate the module's effectiveness, a questionnaire was prepared for teachers to gather student feedback after participating in activities using the Kinetic Vision 3D-printed kits and related materials. Figure 4 illustrates the developed modules and game cards.

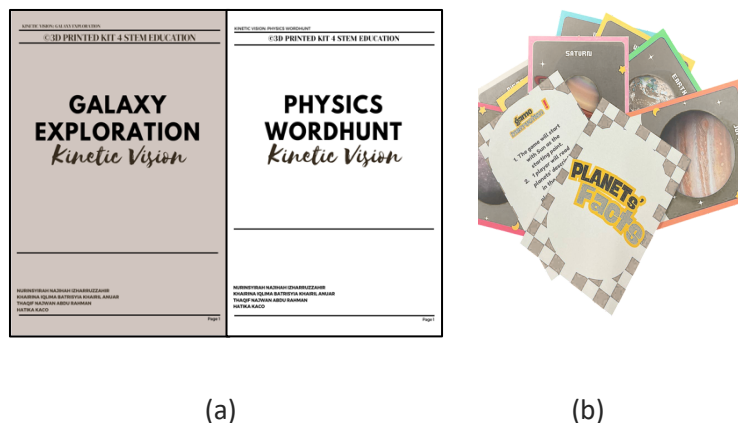


Fig. 4 (a) Developed modules and (b) game cards used with the Kinetics Vision 3D-printed instructional kits

1.3 Implementations

The developed 3D-printed kits *Galaxy Exploration* and *Physics Wordhunt* modules were implemented with a cohort of 85 primary school students at SK Tangga Batu, Melaka, Malaysia. During the implementation, facilitators introduced scientific theories and concepts through hands-on demonstrations utilizing the 3D-printed kits. This experiential learning approach aimed to enhance student engagement and understanding [7,15]. Fig. 5 presents a visual documentation of the implementation process and evaluating the impact and effectiveness of the modules, a structured survey was administered to the participants upon completion of the activities.

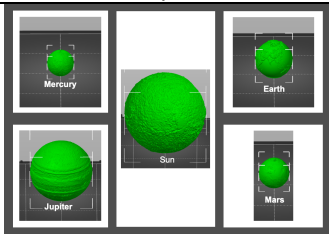
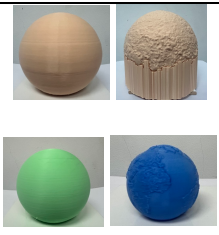
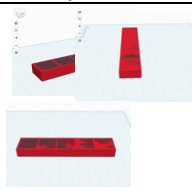
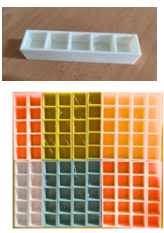
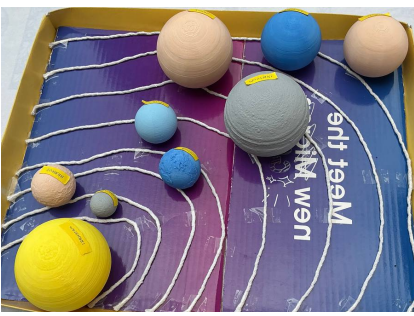








3. Results and Discussion

3.1 Kinetic Vision Kits: Toolpaths and 3D Printed Models

Table 1 displays the digital modelling and toolpaths for each component of the *Galaxy Explorations* and *Physics Wordhunt*. The toolpaths and the digital modelling process involved creating all the planets of *Galaxy Explorations* and the puzzle box and alphabets for *Physics Wordhunt* and assembled to be utilized in the developed game activities using the game cards.

Table 1
 Digital modelling of galaxy exploration and physics wordhunt

Galaxy Exploration		Physics Wordhunt	
Toolpaths	3D Printed Models	Toolpaths	3D Printed Models
			
<i>Planets</i>		<i>Puzzle Box</i>	
  <p style="text-align: center;"><i>Assembled Galaxy Explorations</i></p>		 	<i>Puzzle Words</i>
		   <p style="text-align: center;"><i>Assembled Physics Wordhunt</i></p>	

3.2 Developed Module and Game Card

The activities and 3D printed kits were carefully designed to align with the Physics topic on gravitation, providing an engaging and hands-on learning experience for students. These materials include 3D printed planetary models and a Physics-themed word hunt, both of which serve to reinforce key concepts related to gravitational forces and celestial bodies. As shown in Fig. 6, participants used a specially designed game card featuring a series of structured questions. These included both factual questions about planets and conceptual questions on gravitational principles,

prompting students to apply their knowledge in a playful, inquiry-based approach. The module and game card are designed to connect theoretical learning with hands-on, interactive elements, helping students develop a deeper understanding of core Physics concepts and improve retention through active learning strategies [10,29].



Fig. 6. (a) Kinetic vision modules and (b) Kinetic vision game card

3.3 Students' Perception of the Activity

Fig. 7 summarizes the students' perceptions of the activities using the Kinetic Vision modules and 3D-printed kits. The preliminary implementation showed a strong engagement and positive learning outcomes which in line with recent research on active learning strategies conducted by other research [5,8,31]. Fig. 7(b) demonstrated that 100% of the participants feel that the activities designed in the module are interesting and enjoyable. The results also parallel to the feedback (100%) on they need other future sessions for this kind of experiential learning approach. However, only 62% said they would recommend the activities to others. As for the learning impact shown in Fig. 7(b), the 3D printed kits were particularly effective, with 44% of participants reporting improved understanding of Gravity and Planetary systems which supporting earlier studies on the benefits of tactile learning tools [27]. Additionally, 72% of students rated the kits as very helpful, and the 3D-printed planet models were seen as the most impactful kits by 72% of participants as demonstrated in Fig. 7(c) [14]. Soft skills development was also assessed and the analysis was shown in Fig. 7(d). It was found that about 66.5% of students reported obtained in teamwork and leadership, measured through a post-activity survey where participants rated their growth in collaboration, leadership, and critical thinking based on a Likert scale. Meanwhile critical thinking showed more varied results, the activity clearly supported collaboration and leadership, suggesting additional support could further strengthen critical thinking. Overall, the findings indicate that these activities support both cognitive understanding and affective learning [7].

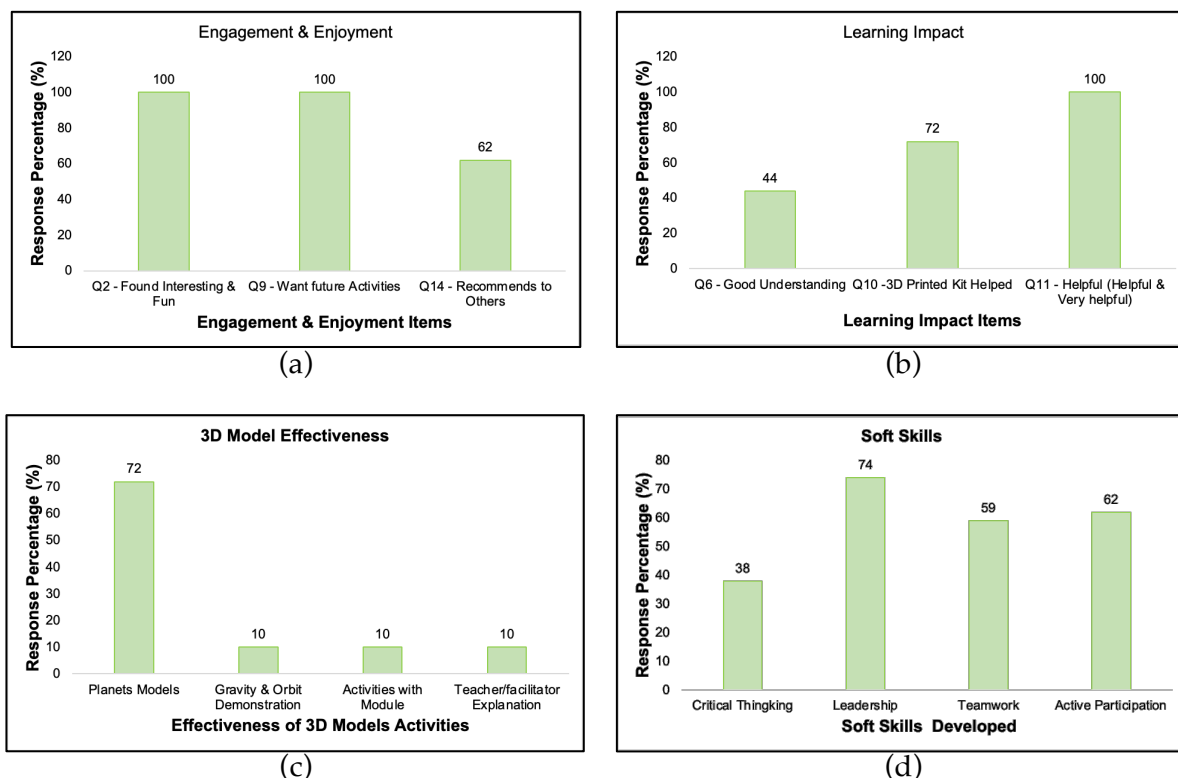


Fig. 7. Student's perception on item related to (a) Engagement and enjoyment, (b) Learning impact, (c) 3D model effectiveness and (d) Soft skills

4. Conclusion and Recommendations

In conclusion, the utilization of 3D printing technology in physics education, through the Kinetic Vision kit, has shown to be an effective way to help students understand abstract concepts like the solar system and gravitation. It offers hands-on, visual, and interactive experiences, the module not only improved conceptual understanding but also made learning more engaging and enjoyable. The students reported that the activities helped them visualize ideas better and fostered teamwork and leadership skills. However, the findings also suggest that critical thinking could benefit from additional support within the module. Future studies could explore the long-term effects of such activities, extend them to other physics topics, and compare outcomes with traditional teaching methods. Overall, this study demonstrates that student-centered, 3D-printed learning tools can make complex STEM subjects more accessible, meaningful, and relevant to learners in today's learning environment.

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