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Issues and Challenges in Teaching Secondary School Quantum Physics with Integrated STEM Education in Malaysia

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Abstract

The emphasis on STEM education in the physics curriculum moves toward addressing the 21st-century demands, but its implementation is fraught with issues and challenges. This paper exposes teachers' and students' concerns and problems with integrated STEM education implementation and relates them to the anticipated problem in quantum physics (QP) learning and facilitation (L&F) in secondary school. The QP L&F challenges include the odd ontological worldview and abstractness of concepts, which have created serious misconceptions among teachers and students. A solution is proposed to address this difficulty, including applying an interactive simulation and a hands-on experiment. This paper also proposes a theoretical framework for developing an instructional module to cater to meaningful QP learning with integrated STEM elements. The proposed theoretical framework has several advantages, including guidance in planning an instructional module applicable to classroom activities and explaining the topic using an inquiry-based learning (IBL) approach with learning activities coordinated using the 5E Instructional Model. Nonetheless, further research is necessary to study the instructional module's development, usability, and L&F effectiveness in the classroom.

Keywords: integrated stem education, quantum physics, learning and facilitation, secondary school

Introduction

In an era of rapid technological advancement, Malaysia is striving for a developed nation to create a scientific, progressive, creative, and prudent society that is crucial in developing future scientific and technological civilizations (Academy of Sciences Malaysia, 2017; MOE, 2018; MOSTI, 2013, 2017). The Ministry of Education believed that these qualities and literacy in Science, Technology, Engineering, and Mathematics (STEM) must be developed to achieve this goal (Farihah Mohd Jamel et al., 2019; Maruthai, 2019; MOE, 2018; MOSTI, 2017).

Along with the aspirations, the Secondary School Curriculum Standards *(KSSM)* was enacted, replacing the Secondary School Integrated Curriculum *(KBSM)* to meet the new policy requirements under the Malaysia Education Blueprint (PPPM) 2013-2025 to ensure that the secondary school curriculum is comparable to international standards (Farihah Mohd Jamel et al., 2019; MOE, 2018). Hence, with a holistic approach, the Curriculum and Assessment Standards Document *(DSKP)* is created to guide teachers in implementing learning and facilitation (L&F) in the classroom.

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The physics *DSKP* highlighted student-centred learning approaches to develop 21st century skills and train students to be competent in the rapid technological growth era and the Industrial Revolution (IR) 4.0 challenges (MOE, 2018). Apart from that, the QP topic is included in the curriculum (MOE, 2018) to expose students to modern physics' perspective and its contribution to the advancement of modern technology such as computers, smartphones, lasers, Global Positioning System (GPS), and Magnetic Resonance Imaging (MRI) (Henriksen et al., 2014; Krijtenburg-Lewerissa et al., 2018; Park et al., 2019). QP has been highlighted as an important topic for secondary school (Krijtenburg-Lewerissa et al., 2018; Moraga-Calderón et al., 2020; Polatdemir et al., 2004) as a fundamental and modern aspect of physics (Moraga-Calderón et al., 2020) that forms the cognitive basis for a proper interpretation of microscopic matter (Kalkanis et al., 2003), which has gained social prominence (Mashhadi & Woolnough, 1996; Michelini et al., 2002; Schleich et al., 2016; Sutrini et al., 2019).

With the inclusion of QP in the physics curriculum, integrated STEM education can be a good strategy to create active and meaningful QP learning as STEM education is the most highlighted in the current education setting (Amelia & Lilia Halim, 2019; Bunyamin, 2015; Shahali et al., 2015), whereby the MOE strives in empowering STEM education through national transformation agenda which is now in the second wave (2016-2020) phase to cultivate public interest and awareness of STEM through campaigns and collaboration with relevant agencies (Amelia & Lilia Halim, 2019).

Literature Review

Issues pertaining to integrated STEM Education implementation

Malaysia depends on knowledgeable workers in driving the economy and handling the uncertainties in the IR 4.0 era (Academy of Sciences Malaysia, 2017). However, generating a workforce for STEM-related and technology-based future jobs is challenging as studies show that the number of qualified workers has been declining over the years (Academy of Sciences Malaysia, 2015, 2017; Shahali et al., 2015). The current analysis shows that students' interest in the STEM field has decreased, whereby only 44% of students took STEM compared to 49% in 2012, equivalent to an average reduction of about 6,000 students per year (MOE, 2019). With this analysis, it is perceived that the current rate of student entry into STEM studies at the higher and secondary levels would be insufficient in supplying qualified staff to meet the aspired projections or develop the expected knowledge-driven, value-added economy (Academy of Sciences Malaysia, 2017).

Meanwhile, the major national examinations' quality is only average, making pedagogies questionable in addressing the millennial learning trend (Academy of Sciences Malaysia, 2017). This issue may be related to the lack of competencies among teachers in conducting integrated STEM education, as the survey conducted by the Academy of Science Malaysia (2017) shows that nearly 47% of STEM secondary school teachers did not receive STEM training since its introduction to school. However, Malaysia is new to integrated STEM education (Maruthai, 2019), and there is no official curriculum yet (Amelia & Lilia Halim, 2019). The STEM education implementation guide (MOE, 2016b, 2016a) does not provide specific STEM performance standards apart from the *DSKP* for each subject. By far, the learning specification streaming system for students is branded as a STEM package (Edy Hafizan et al., 2017; MOE, 2016b), which is similar to Martín-Páez et al. (2019) study in terms of STEM elements integration, where learning involves integrating conceptual, procedural, and attitudinal through a group of STEM skills with a real-world problem-solving approach.

Another ongoing issue in the Malaysian education system is the workload of teachers, where their duties involve not only preparing and planning for L&F but also clerical tasks such as data entry, inventory, students' data management, and a continuous engagement with school events that are scheduled and coordinated throughout the year, which restrain teachers from preparing for meaningful lessons (Abdullah et al., 2017; Nur Farhana Ramli & Othman Talib, 2017; Siew et al., 2015). It was worsening when teachers rushed to finish the syllabus within the timeline to prepare students for the examinations,

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especially the national examination, *Sijil Pelajaran Malaysia (SPM)*, which had caused burnout among teachers (Nur Farhana Ramli & Othman Talib, 2017).

Apart from that, students have been trained and drilled to answer questions that are already set with a familiar pattern in an examination-oriented education system, which encourages memorization (Ro, 2018). For instance, this method may help students pass and score in the examination but does not add up to STEM skills, such as real-world problem-solving, critical thinking, and science process skills (Chin et al., 2019; Porcaro, 2011). Thus, promoting and nurturing an integrated STEM education culture should be emphasized to provide students with opportunities to develop their potential. Simultaneously, teachers must possess the knowledge and skills necessary to have a positive impact on students (Pearson, 2017).

Challenges in teaching Quantum Physics with integrated STEM Education

Science, technology, and Innovation (STI) are essential keys to national economic growth and social progress, which brought STEM education into the main agenda in education transformation (Academy of Sciences Malaysia, 2015, 2017; MOSTI, 2017). The rapid advancement in this field instigates the education system to evolve, and thus, teachers must progress too to be useful and effective in executing the education transformation (Abdullah et al., 2017; Academy of Sciences Malaysia, 2017; MOE, 2016a). In realizing the aspiration, teachers are advocated to conduct instructional strategies that can engage students in challenging, enjoyable, and meaningful learning activities to attract more science stream students (MOE, 2016b, 2018). In this manner, teachers need to be well-equipped with pedagogical skills that include integrated STEM education to meet the 21st-century demands (Abdullah et al., 2017; Wan Norhasma & Nurahimah, 2019).

However, integrating STEM education is difficult because traditional instructional approaches have presented STEM disciplines separately, with a distinct and inconsistent collection of facts and skills (English, 2016; Pearson, 2017). Teachers are expected to bridge the boundaries between STEM disciplines in this situation (Shahali et al., 2015). Besides, they must understand the intent of integrated STEM education and clearly demonstrate how it can be accomplished while ensuring that all STEM elements are integrated with learning activities that help students master the necessary skills (Pearson, 2017).

In physics KSSM particularly, teachers are expected to implement the integrated STEM education approach in learning and facilitation (L&F) (MOE, 2018) and expose students to real-life problem-solving, community, and environmental issues (Edy Hafizan et al., 2017; MOE, 2016b). The inadequacy of skills in this area made it challenging for teachers to pursue, which had caused inconsistent teaching and learning quality (Academy of Sciences Malaysia, 2017).

For QP learning with integrated STEM education, it is anticipated to be more challenging because this newly added topic is different from classical physics and has a long unclear interpretation in history (Angelo et al., 2014). Due to the confusing QP ontology, it is challenging for teachers to transfer the knowledge (Ab Rahman & Phang, 2012; Bungum et al., 2015; Shi, 2013; Stadermann & Goedhart, 2020). Besides, teachers must master the QP fundamental concepts with some mathematical formalism before transferring them to students (Angelo et al., 2014). In particular, what challenges a teacher is how to teach the wave-particle duality and the photoelectric effect experiment effectively. In these topics, teachers need to guide students to understand the particle nature of light and the concept of a photon (McKagan et al., 2009; Supurwoko et al., 2017) and address the gap between classical and quantum concepts of waves, particles, and uncertainty by emphasizing their differences in the classical and quantum world (Rodriguez, 2018).

While QP is challenging due to its nature, integrated STEM education, on the other hand, challenges teachers in carrying out appropriate learning activities with QP knowledge. Thus, the ability to integrate STEM disciplines and elements is required, which develops students' capacity to comprehend the QP concept and acquire skills by applying the concepts and adding attitudinal values through their learning experience.

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The current textbook does not specify instruction or activity that involves STEM activities for the QP topic (Chuan et al., 2020). Teachers with limited information about integrated STEM education may become dependent on a textbook, following a brief instruction of the suggested activities which is not paying sufficient attention to essential skills such as problem-solving, application of the principle, interpreting and predicting (Academy of Sciences Malaysia, 2015; Toma & Greca, 2018). Insufficient knowledge, especially in engineering and technology discipline, also demotivated teachers from pursuing integrated STEM education, thus adhering to their teaching routine (EL-Deghaidy et al., 2017; White, 2014).

In rural and suburban areas where schools lack facilities such as internet connection, laboratory and educational resources, teachers may struggle to implement integrated STEM education (Academy of Sciences Malaysia, 2017; Siew et al., 2015). In this situation, it is anticipated that it will be more challenging in QP learning as this topic is better learned with technology application to visualize the abstract concepts (Kohnle et al., 2012; McKagan et al., 2008; G. Ravaioli, 2019).

The anticipated difficulties in Quantum Physics learning

QP in the physics curriculum introduces the fundamental concepts, which comprises the quantum theory of light, wave-particle duality, photoelectric effect, and Einstein photoelectric effect (MOE, 2018). This topic concentrates more on conceptual understanding than complicated mathematics formulation to cater to its suitability (Chuan et al., 2020). Since QP is new in the physics curriculum, local research on instructional strategies is hardly found in search engines. However, numerous researches have been done overseas, which is crucial in informing about the ongoing trends and issues in QP teaching and learning.

In contrasting QP from classical physics (Krijtenburg-Lewerissa et al., 2017), Mashhadi and Woolnough (1999) explained that classical physics basically rely on macroscopic observations and concepts are chosen for intuitive visualization. On the other hand, quantum phenomena are dominant at the microscopic level, which has led to the intuitive violation of concepts. For example, the entity located in space is called a particle, an intuitive concept that has presumably passed from the macroscopic to the microscopic (Mashhadi & Woolnough, 1999). Another example is the quantization of energy, a fascinating aspect that significantly differentiates QP from the classical view but is confusing to grasp (Cuppari et al., 1997).

Although QP often intrigues young students (Bøe et al., 2018; Bungum et al., 2015; Johansson et al., 2018; Myhrehagen & Bungum, 2016), many researchers and educators reported that this topic is difficult for students to understand (Dutt, 2011; Malgieri et al., 2017), which classified by Malgieri et al. (2017) as conceptual difficulties because they are intuitive, which require qualitative reasoning and mental models of the students. Due to a different paradigm, even though students have a strong knowledge of classical physics, they became novices when QP was introduced, and the knowledge structure had to be gradually established (Singh & Marshman, 2015). This situation is common as teachers also encountered the same problem (Kızılcık & Yavaş, 2016). Additionally, the quantum world is difficult for students to explore independently, and the majority of misconceptions are formed after the learning experience due to their inability to apply it to everyday practice (Testa et al., 2020). Wave-particle duality, photon, electron, the uncertainty principle, and photoelectric effect are among the problematic concepts often mentioned by researchers (Dutt, 2011; Krijtenburg-Lewerissa et al., 2017; Olsen, 2002).

Other difficulties reported were concerning students' visualization of the experiment results, which involves a challenging mathematical calculation to interpret an experiment (Cataloglu & Robinett, 2002; Mashhadi & Woolnough, 1999). Besides, its epistemology is somehow illogical and abstract, disconnected to everyday living, has no direct experience with the phenomenon, and often relying on simplified abstract models to develop conception (Cataloglu, 2002; Dangur et al., 2014; McKagan et al., 2008). As a result, the nature of QP had caused serious misconceptions among students. Furthermore, the topic is new to secondary school students and is disconnected from classical physics (Hadzidaki et al., 2000).

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As seen in the wave-particle duality conception, students developed misconceptions mostly impacted by other areas of knowledge, such as common sense and classical physics (Olsen, 2002), where students' conceptual frameworks were overlapped and mixed with classical physics and quantum mechanics. For example, the Newtonian-based deterministic worldview imposes their newfound knowledge (Hadzidaki et al., 2000; Kalkanis et al., 2003; Stadermann & Goedhart, 2020).

Student's misconceptions are also caused by a direct implication of teaching (Olsen, 2002). Traditional teaching often employs pedagogical analogies or metaphors that refer to daily life images, such as electron clouds for the atomic spatial location of bound electrons or bright spherical balls model to represent the quantum entity. This mental image, which is also shown in the textbook, is confusing when students try to relate to the QP concept, which they never encountered (Kalkanis et al., 2003; Krijtenburg-Lewerissa et al., 2017). Other studies also have shown that the appearance of the wave-like behavior of electrons distributed as merely bright spots had caused the students to think that the wave-like behavior is a cloud of spattered charge (Müller & Wiesner, 2002). These mental images or models were wrongly understood as students failed to understand the atomic model's energy quantization concept (Taber, 2005).

The atomic Bohr model and the development of instructional physics models that modeled electrons as negatively charged tiny billiard balls also influenced student perception of QP (Stadermann et al., 2019; Stadermann & Goedhart, 2020). Students tend to explain electrons using a classical planetary model, as shown in the Bohr atom model (Stadermann & Goedhart, 2020), and the representation students make in the classroom often corresponds to everyday experiences materials (Kalkanis et al., 2003). While in the double-slit experiment for electrons, the interference pattern formed shows electrons are a wave and not as miniature billiard balls or particles (Sayer et al., 2017). The electrons representation is confusing to students as they lack of a useful framework to contrast explainable physical laws (Stadermann & Goedhart, 2020). The QP ontological supposedly correspond to what could be termed as 'quantum objects' with specific characteristics. When traditional teaching methods use a mechanical analogy, it has led to particles being treated as ordinary material objects without discriminating the ontological conditions (Kalkanis et al., 2003).

As discussed, most of the issues that influence students' difficulties in understanding QP are the quantum theories' ontological and epistemological views. Malaysian secondary school students may experience these difficulties, and they need to be addressed to eliminate the causes of misconception in understanding QP concepts. In the study of creating better learning of QP's epistemology and cognitive approach, Ravaioli et al. (2018) emphasize visualization, comparability, and ontology in instructional strategy, which are discussed further in the next section.

Proposed solution and Theoretical Framework

More research has been conducted to minimize QP instructional difficulties (see: Bungum et al., 2015; Kohnle, 2010; McKagan et al., 2007, 2008; Ravaioli, 2019; Singh, 2008; Sokolowski, 2013; Supurwoko et al., 2017). It is also highlighted that an alternative to the teacher-centered learning strategy, a conventional strategy (Kunnath, 2017; Marshman & Singh, 2015; Zollman, 1999) known as direct instruction (Mansyur & Darsikin, 2016), is needed as it was seen that the traditional strategy is not sufficient in helping students understand abstract concepts like QP (Gonen, 2006; Hubber, 2006; Sayer et al., 2017)) and had caused students to become passive learners (Francisco, 2013).

As aforementioned, QP is indeed a tough and elusive topic, difficult to understand than classical physics. Hence, it requires a specific approach to tackle the problems (Habibbulloh, 2019; López-Incera & Dür, 2019; Krijtenburg-Lewerissa et al., 2017; McKagan et al., 2009; Stadermann & Goedhart, 2020). Integrated STEM education philosophy in empowering cohesive teaching and learning paradigm may encourage and arouse students' interest in QP with real-life contexts and common technological applications (Stadermann et al., 2019).

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Many studies have used the real-world situation in QP learning activities and agreed that it could enhance students' conceptual understanding (Escalada et al., 2004; McKagan et al., 2009; Michelini et al., 2004; Tarng et al., 2018). The use of instructional technology that utilizes computer-based technology in pedagogical instruction, including interactive simulation, and videos, can be advantageous for abstract concepts (White, 2014). In particular, a hands-on activity called Hallwachs' experiments (Ravaioli, 2019) and the photoelectric effect simulation, an interactive virtual lab from PhET (Physics Education Technology) (McKagan et al., 2009) can be utilized in facilitating the students' conception of QP. Several studies have used and recommended these materials as practical tools that can promote inquiry learning in challenging classical physics reasoning by contrasting quantum theory with the classical view (McKagan et al., 2009; Ravaioli, 2019). Hence, these materials can be studied thoroughly to utilize them optimally in classroom activities.

It was seen that the photoelectric effect experiment could improve QP teaching by minimizing the abstractness and facilitate the interpretation of phenomena that could increase students' motivation (Didiş et al., 2014; Michelini et al., 2014). By comparing the classical hypothesis, empirical results, and quantum explanation, this experiment could compare classical physics with the quantum view and anticipate the teaching problem (Asikainen & Hirvonen, 2009).

However, learning gains depend on how a teacher delivers the lesson (Kamsi et al., 2019; Zaher Atwa et al., 2016). For students to have meaningful learning, it requires a well-planned strategy, considering essential aspects that contribute to achieving the required goals that parallel to the current education setting. Additionally, instructional materials with a student-centered learning approach like inquiry-based learning can be employed to stimulate students' interest in QP, which is also suited to the STEM learning environment (Murphy et al., 2019; Satanassi et al., 2018). Developmental research can be carried out to develop an instructional module that facilitates teachers to overcome the issues and challenges in QP L&F.

The inquiry-based learning strategy has been recommended by scholars (Bybee, 2013; Thibaut et al., 2018) to promotes active learning and support the use of authentic, real-world problems (Thibaut et al., 2018) in adapting to the current learning ecosystem (Anealka Aziz, 2018). As the education setting evolves, it opens more spaces for empirical research in instructional development. Thus, a theoretical framework is proposed in developing an instructional module for secondary school QP with an integrated STEM education approach in addressing the anticipated challenges in the L&F of the QP topic.

The proposed theoretical framework is divided into three sub-sections that are guided by the design and development research (Richey & Klein, 2007), as shown in Figure 1. The needs analysis study is guided by Mckillip's Discrepancy Model (Chedi, 2017; McKillip, 1987; Mohd Paris Saleh & Saedah Siraj, 2016; Yaakob, 2016) to discover and identify the needs for a QP instructional module in secondary school. With the information in phase 1, the instructional module for secondary school QP with an integrated STEM education approach is designed and developed with five theories and models to support and guide the design and development phase. The constructivism theory (Dewey, 1938; Harasim & Harasim, 2018; Soloway et al., 1996) is the foundation of the instructional and learning approach with the TABA Model (Aydın et al., 2017; Portillo et al., 2020; Taba, 1962) as a guide in structuring and organizing the components and elements in the instructional module that comprises inquiry-based learning and integrated STEM education strategy for the L&F of the Wave-particle duality concept as the content knowledge, and the 5E Instructional Model as a guide in structuring the learning activities. In the final stage of the research, the TUP model (Bednarik, 2002; Bednarik et al., 2004) guides the instructional module prototype's usability evaluation for experienced teachers to evaluate and validate the technological, usability and pedagogical use in assisting QP L&F.

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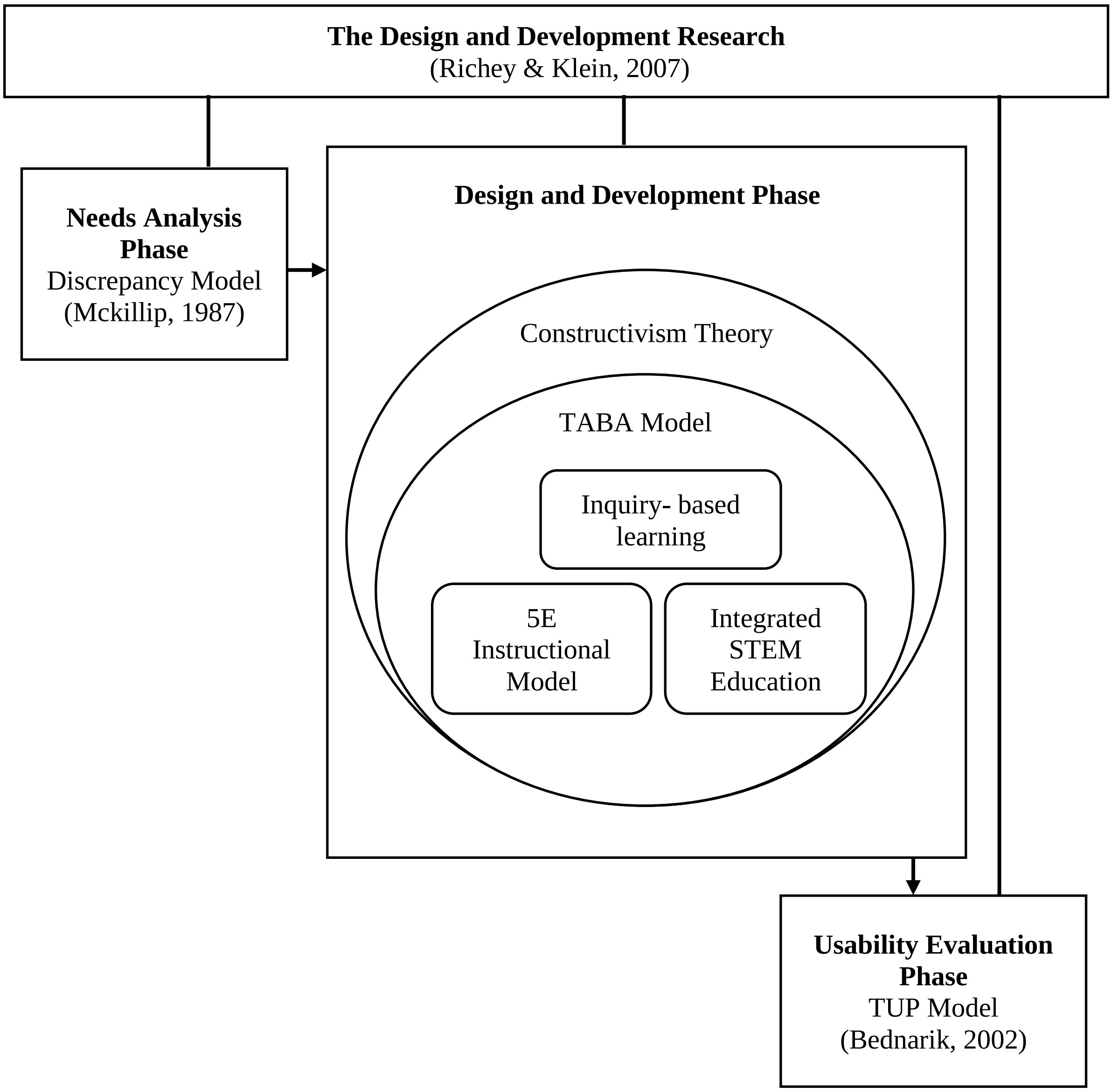
Figure 1: Author's suggestion of the theoretical framework in developing an instructional module for secondary school QP with integrated STEM education



Discussion and Implication

Reviews of the corresponding literature have highlighted several gaps in developing students' understanding of QP in the physics curriculum related to the anticipated learning difficulties and instructional challenges, as well as issues and challenges pertaining to integrated STEM education. The proposed solution and the theoretical framework embrace a constructivist perspective, supporting inquiry-based learning strategies that emphasize active learning in promoting a meaningful learning experience. The instructional module's theoretical framework aims to provide student-centered activities, with the teacher's role as a facilitator. In this regard, an instructional module can be used as an alternative to the traditional approach, encouraging teamwork, critical thinking, innovation, and communication in the classroom while being consistent with integrated STEM education strategies.

This concept paper intends to provide insight into discovering alternatives or solutions to problems by exposing the issues and challenges in implementing integrated STEM education. Besides, the difficulties

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in QP L&F inform researchers and teachers about what to expect in carrying out QP lessons and provide insight in dealing with the issues. By exploring the integrated STEM education approach and strategies, it is possible to incorporate them into QP L&F to develop an instructional module or learning materials. Nonetheless, further research is necessary to investigate these instructional strategies' effects on student's cognitive and affective learning outcomes.

Conclusion

To summarise, the present paper has presented issues concerning the implementation of integrated STEM education, challenges in teaching QP with integrated STEM education, and anticipated difficulties in QP learning. Based on previous literature, techniques such as applying interactive simulation and a hands-on experiment with inquiry-based learning strategy and the integrated STEM education strategy were suggested. A theoretical framework for developing an instructional module for secondary school QP with integrated STEM education provides ideas for the developmental research field. It is hoped that this paper benefit researchers and educators in finding a solution to ensure successful teaching and learning capable of providing a potential solution and insight into the future study.

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