

# HOW STUDENTS UNDERSTAND THE CONCEPT OF KINEMATIC QUANTITIES USING MARBLES: A HYPOTHETICAL LEARNING TRAJECTORY

*COMO OS ALUNOS COMPREENDEM O CONCEITO DE GRANDEZAS CINEMÁTICAS USANDO BOLINHAS DE GUDE: UMA TRAJETÓRIA DE APRENDIZAGEM HIPOTÉTICA*

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## Abstract

Kinematics quantities are fundamental to understanding kinematics, dynamics, and advanced physics concepts such as mechanics. This study uses a traditional marble game to explore how students understand kinematics quantities in contextual problems. This study follows the Gravemeijer and Cobb research design model, which consists of three phases: Initial Design, Design Experiment, and Retrospective Analysis. This study involved 15 prospective elementary school teachers with low, medium, and high academic abilities. Data collection was conducted through analysis of student work documents and in-depth interviews to obtain a comprehensive understanding of the thinking processes and conceptual constructions that emerged during the learning process. The research findings show that students can discover and construct the concept of kinematic quantities. With guidance from lecturers, students completed more structured student work documents in accordance

## Resumo

*As grandezas cinemáticas são fundamentais para a compreensão da cinemática, da dinâmica e de conceitos avançados de física, como a mecânica. Este estudo utiliza um jogo tradicional de bolinhas de gude para explorar como os alunos compreendem as grandezas cinemáticas em problemas contextualizados. O estudo segue o modelo de pesquisa de Gravemeijer e Cobb, que consiste em três fases: Projeto Inicial, Experimento de Projeto e Análise Retrospectiva. Participaram do estudo 15 futuros professores do ensino fundamental com níveis de habilidade acadêmica baixo, médio e alto. A coleta de dados foi realizada por meio da análise de trabalhos escritos dos alunos e entrevistas em profundidade, visando obter uma compreensão abrangente dos processos de pensamento e das construções conceituais que emergiram durante o processo de aprendizagem. Os resultados da pesquisa mostram que os alunos conseguem descobrir e construir o conceito de*



with their thinking processes, which were presented starting from contextual problems to discovering formal physics concepts. In other words, the Hypothetical Learning Trajectory (HLT) can facilitate conceptual understanding and make it easier for students to understand kinematic quantity concepts. The impact of these research results is that the Hypothetical Learning Trajectory (HLT) design can internalize physics concepts in a more meaningful, contextual, and relevant way to everyday life.

**Keywords:** Traditional Games. Ethnophysics. Design Research. Contextual-Based Learning.

*grandezas cinemáticas. Com a orientação dos professores, os alunos elaboraram trabalhos escritos mais estruturados, de acordo com seus processos de pensamento, que foram apresentados partindo de problemas contextualizados até a descoberta de conceitos formais de física. Em outras palavras, a Trajetória Hipotética de Aprendizagem (THA) pode facilitar a compreensão conceitual e tornar mais fácil para os alunos entenderem os conceitos de grandezas cinemáticas. O impacto dos resultados desta pesquisa reside no fato de que o modelo de Trajetória Hipotética de Aprendizagem (THA) pode internalizar conceitos de física de uma forma mais significativa, contextualizada e relevante para o cotidiano.*

**Palavras-chave:** Jogos Tradicionais. Etnofísica. Pesquisa em Design. Aprendizagem Contextualizada.

## 1 INTRODUCTION

Kinematics is a scientific topic that is the foundation for understanding advanced physics concepts, including those taught in university science courses (Planinic et al., 2013), particularly mechanics, which deals with forces acting on objects (Taqwa & Rivaldo, 2018). To understand mechanical concepts, a strong and in-depth conceptual understanding is necessary to avoid misconceptions (Singh & Schunn, 2009). Many ideas are studied in kinematics, such as the quantities in kinematics: distance, displacement, position, velocity, speed, deceleration, and acceleration.

Various studies have been conducted to minimize kinematics misunderstandings, for example, investigating misunderstandings about kinematics concepts and the causes of misunderstandings among prospective physics teacher students (Mellu et al., 2022). Cartoons can improve students' conceptual understanding of kinematics concepts (Defianti & Rohmi, 2021). Using GeoGebra software facilitates students' understanding of kinematics concepts (Halim et al., 2021). Virtual reality-based games that actively engage students in learning can improve their understanding of kinematics concepts (Cruz et al., 2023). Contextual learning processes are crucial in understanding abstract physics concepts and can help overcome misunderstandings (Guffey & Slater, 2020).

The traditional game of *Patil Lele*, a local cultural element closely related to everyday life, can reveal key concepts in physics, including Newton's laws, momentum, impulse, moment of force, and parabolic motion (Rohmah et al., 2024). The traditional game of *Taloe Yeye* from Aceh teaches physics lessons by explaining business and energy concepts (Nurianti et al., 2023). Educators can use traditional games as pedagogical tools to help achieve learning objectives (Pic et al., 2019). The results of this study indicate that the traditional game of *Luksong Baka*, which originated in the Philippines and involves physical concepts such as force, impulse, and momentum change when jumping, can be an effective means of strengthening understanding of scientific concepts while preserving local cultural values (Ferolino & Marasigan, 2022). The results of the study show that traditional Canary Islands games such as *la pina and billarda*, which use simple objects as a medium of movement, naturally represent physical concepts such as force, momentum, and motion dynamics, thereby becoming a contextual means of understanding scientific principles through local cultural activities (Luchoro-Parrilla et al., 2021). In the marbles game, the concept of kinematic quantities can be explained to students so they can gain hands-on experience (Kreinsen, 2024). This can be used as a starting point for understanding, rediscovering, and building concepts of kinematic quantities.

To build a deep understanding of concepts, the learning process needs to be systematically designed to facilitate students' discovery and construction of these concepts (Gravemeijer, 2004; Sarama & Clements, 2019). Therefore, a learning path based on an ethnoscience approach is needed to help students discover the concept of kinematic quantities. This learning trajectory consists of a series of steps that begin with introducing a real-world context and then using that context to rediscover physics concepts until students ultimately understand the concepts in a standardized form. Furthermore, the outcome of this learning is that students can understand the relationship between science, culture, and everyday life, become familiar with the applications of physics, and help eliminate previously held misconceptions. Therefore, this research is expected to provide an overview of students' learning trajectories through traditional marbles game activities.

Learning design can take the form of a learning trajectory, viewed as a strategic step in improving the quality of the learning process to achieve established goals (Simonson, 2006). The concept of a learning trajectory was first introduced by Simon

(1995) in the field of education using the term Hypothetical Learning Trajectory (HLT). HLT includes three main components: (1) learning objectives, (2) learning activities or scenarios, and (3) hypotheses regarding the student's learning process.

The novelty of this study lies in the integration of traditional marbles as a local context in teaching kinematics concepts and the application of Hypothetical Learning Trajectory (HLT) to facilitate students' concept construction. This research also provides an empirical model of how culture-based activities can be used as a means of exploring abstract physics concepts, thus offering a new alternative in the design of ethnoscience-based physics learning. This research also serves as a bridge between science and the local cultural context. Through this approach, it is hoped that students can internalize physics concepts in a more meaningful, contextual, and relevant way to the realities of everyday life.

## **2 METHOD**

This research adopts the design research model developed by Gravemeijer and Cobb (2006), which includes three main phases: (1) preliminary design, (2) the design experiment, and (3) retrospective analysis. This research used a qualitative descriptive approach to achieve the research objectives: assess students' understanding of kinematic quantities and examine the role of the HLT in facilitating this understanding.

### **2.1 Preliminary Design Phase**

The initial step in this research was to formulate learning objectives related to kinematic quantities. Based on the literature review, the learning objectives for kinematic quantities emphasize students' ability to understand fundamental kinematic concepts. To identify the starting point for learning, researchers conducted a diagnostic test on 15 prospective elementary school teachers using the Force Concept Inventory (FCI) instrument adapted to the context of kinematic quantities. The results of the diagnostic test analysis indicated that most students still experienced misconceptions and difficulties in understanding concepts within a scientific theoretical framework. Based on these findings, researchers then formulated the HLT for kinematic quantities as the basis for designing and implementing learning in the next experimental phase.

## 2.2 The Design Experiment Phase

The primary focus of phase two is to test and improve the effectiveness of the designed Hypothetical Learning Trajectory (HLT). At this stage, the HLT has the potential to develop into a localized instructional theory specifically designed to facilitate the learning of kinematic quantity concepts. This phase is cyclical, where theoretical thinking and learning experiments are interconnected and iterative (Gravemeijer & Cobb, 2006).

Prior to the classroom experiment, the HLT design was developed in collaboration with design research experts. This study involved three experts in the development of HLT in design research. To ensure the physics concepts presented in HLT, two experts and a university-level education practitioner validated aspects of physics material to ensure content appropriateness and teaching relevance. The active involvement of experts and practitioners ensured that the HLT design was not only theoretically sound but also feasible and realistic to implement.

The teaching experiment in the implementation of HLT design involved three randomly selected prospective elementary school teachers, taking into account variations in academic ability (high, medium, and low) based on the results of the initial FCI diagnostic test. Research data were collected through student work documents and in-depth interviews conducted during the learning process to analyze whether the actual conditions were in line with the assumptions contained in HLT. The interviews aimed to explore how students understood the learning objectives of the activities given, while also examining the extent to which the lecturer's anticipation and probing questions could guide students in discovering and constructing concepts.

## 2.3 Retrospective Analysis

The term "retrospective analysis" literally comes from the words "retro" (backward) and "spectare" (to see), meaning "to look back." Retrospective analysis is a data analysis approach that involves reviewing (reflectively and analytically) past events, experiences, processes, or data to identify patterns, meanings, or relationships relevant to the research focus (Smith, 1998). At this stage, researchers review all data collected during the implementation process to understand how the HLT design works and how

students develop their understanding. Researchers compare HLT predictions with actual findings during the learning process.

### 3 RESULTS

#### 3.1 Preparing the preliminary design

The preliminary design phases is the main foundation in the design research process that aims to achieve the learning objectives that have been formulated. At this phases, researchers develop a systematic and gradual learning flow to facilitate students in discovering and building their own understanding of kinematic concepts. This design is based on the principle that effective learning must start from a concrete context and move towards abstract understanding through a series of meaningful and structured activities.

To achieve this goal, contextual activities were designed, namely playing marbles, which was used as a starting point for learning. At this stage, students are asked to play marbles in a triangular formation, then observe the movement of the marbles that are shot to identify and measure their position, distance, and displacement. Through this observation, students are expected to be able to compare and interpret the differences between these quantities based on their direct experience in the field. This part is the basic part that describes the students' thinking stages in the concept construction process of the iceberg model. Figure 1 illustrates the tip of the iceberg of the HLT concept regarding kinematic quantities.

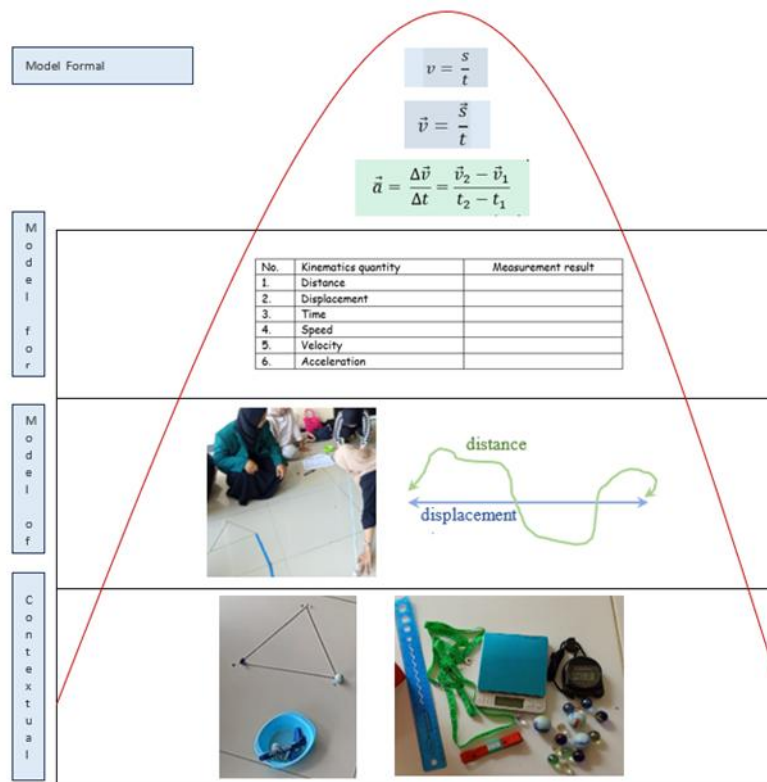
The next layer of the iceberg describes the model-of stage, which is the process of representing concrete phenomena in the form of conceptual models. At this stage, students take more systematic measurements and describe the trajectory of the marbles based on the observation data. This activity serves to connect empirical experience with simple scientific modeling, so that students begin to understand the relationship between distance, time, and speed qualitatively.

The next stage is model-for, which is the process of abstraction from the initial model. In this phase, students are able to use their observations to calculate the values of average speed and velocity, as well as determine the acceleration and deceleration that occur during the movement of the marble. In addition, students begin to realize the

importance of direction in determining the vector properties of velocity and displacement. Through this activity, students move from phenomenological understanding to quantitative conceptualization.

The tip of the iceberg represents the highest level in the conceptualization process, where students are expected to be able to use formal physics notation related to kinematic quantities and their international units (SI). At this stage, students not only understand the phenomenon of motion descriptively, but can also represent it symbolically using correct physics formulas and equations. Thus, the iceberg model in the HLT design serves as a conceptual map that guides students through the stages of thinking from concrete to abstract, while ensuring that each stage of learning is logically related to previous learning experiences. This model also allows lecturers to provide appropriate scaffolding at each stage, so that the learning process is more meaningful, contextual, and in line with the way prospective elementary school teachers think.

Figure 1. Kinematic quantities in the marble game on the iceberg

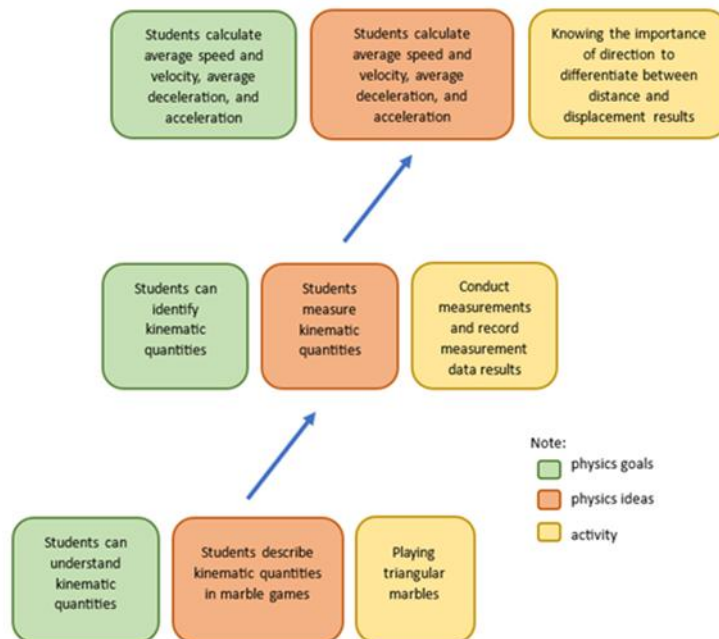


Source: Author's own elaboration

The visual workflow of the HLT concept on the topic of kinematic quantities is shown in Figure 2, illustrating the integration of objectives, conceptual ideas, and learning activities that are systematically designed to shape the learning flow of students in

understanding kinematic concepts. In general, this workflow consists of three main components. First, learning objectives, which contain descriptions of the expected learning outcomes of students. These objectives focus on students' ability to rediscover and build conceptual understanding of kinematic quantities such as position, distance, displacement, velocity, speed, acceleration, and deceleration through direct experience in the context of marbles. Second, the ideas, which are conceptual ideas formulated by researchers based on the HLT theoretical framework and constructivist principles. These ideas are arranged in stages according to their conceptual complexity, from concrete phenomena to abstract forms, to provide instructional solutions that support the achievement of learning objectives. At this stage, the researchers' thinking is directed towards anticipating possible patterns of student thinking and developing learning strategies that can facilitate the formation of scientific meaning through empirical experience.

Figure 2. Workflow visual HLT kinematic quantities



Source: Author's own elaboration

Third, activities, which are a series of learning activities carried out using marbles as the main medium. These activities are designed so that students can observe, measure, and analyze motion phenomena directly. Through these activities, students are encouraged to make initial assumptions (hypothesis generation) related to the concepts of magnitude, measuring instruments, and units used. During the implementation of HLT,

every assumption or prediction made by students will be responded to through anticipation and probing questions from the lecturer. These guiding questions serve as a form of pedagogical scaffolding to help students review their understanding, correct conceptual errors, and guide them towards a more scientific construction of concepts. Thus, the interaction between students and lecturers not only serves as a process of clarification, but also as a reflective mechanism that strengthens the process of concept internalization. The HLT workflow which not only illustrates the sequence of learning activities but also reflects the dynamics of thinking and interaction expected to occur during the learning process. It serves as a conceptual guide for lecturers in managing a progressive, contextual, and meaningful scientific discovery-based instructional process.

### **3.2 Conduct the design experiment**

The learning activities designed at this stage aim to help students understand the concepts of kinematic quantities through a traditional marble game with a triangular pattern. Before the activity began, the lecturer gave an initial briefing by asking students to carefully read all sections of the Student Worksheet (SW), which included implementation instructions, learning objectives, supporting information, activity steps, and problem-solving stages arranged from simple to complex levels. The worksheet is given to three students with different academic ability categories; low, medium, and high. The lecturer designs the SW according to the students' thought processes based on the HLT principle, so that each activity presented is able to facilitate students to rediscover kinematic concepts through the concrete experience of playing marbles. Thus, the SW serves not only as an activity guide but also as a diagnostic instrument to trace students' thinking processes and concept construction in stages.

#### **3.2.1 Students with Low Academic Ability**

Students with low academic ability showed difficulty in understanding the instructions and questions listed on the worksheet. This was evident from their inaccurate answers and information that was not relevant to the context of the problems given. Based on the interview results, students in this category needed a relatively long time to group physical quantities and determine the formulas relevant to the observed phenomena. They

are also unfamiliar with the names of some of the measuring instruments used in the activity, as well as the units of measurement used in the calculations. These findings indicate that students with low abilities are still in the early stages of understanding the relationship between motion phenomena and symbolic representations in physics. Ignorance of measuring instruments and units indicates that students are not yet able to systematically connect empirical experiences with scientific concepts. Therefore, at this stage, the role of lecturers is very important in providing scaffolding through guiding questions and conceptual clarification to help students reconstruct the scientific meaning of their observations.

The next section presents excerpts from interviews between lecturers (L) and students (S) that describe the thought processes and difficulties experienced by students in understanding the basic concepts of kinematic quantities through traditional marble games.

*L: Could you complete the activity steps and understand the questions?*

*S: Yes, ma'am. I've made a triangle on the ground, arranged marbles of varying sizes at each corner, and in the center according to the instructions. Then I shot several marbles at the "target" marble. After that, I tried to redraw the marbles' paths from start to finish.*

*L: Did you find the distance between the marbles after the shots?*

*S: The distance from point A to C is this long, ma'am (student shows a picture of the trajectory of marble A to C).*

*L: How do I calculate displacement?*

*S: Hmm (student thinks for a long time), pointing out that the displacement is when marble B moves to D.*

*L: Look again at the movement of marble A to C. Can you show the displacement?*

*S: The student is confused and thinks for a long time, then answers that the displacement is from marble A to C.*

*L: So distance and displacement are the same thing here, huh? Let's look again; is there any influence between the two?*

*S: Hmm (student thinks for a long time).*

*L: Okay (ask a probing question). If a marble is fired in a semicircular trajectory and stops precisely at the point of impact, does its motion have a zero value? Explain?*

*S: Pause while repeating the question (it takes time). Then answer, "It could have a zero value." But I can't explain why.*

*L: Are you able to determine the initial and final positions?*

*S: Yes, ma'am. The initial and final points are the same.*

*L: Does it affect the marble's motion?*

*S: That's right, ma'am. It's affected by direction, while distance isn't.*

*L: Can you conclude what distance and change are from your experience playing marbles?*

*S: Distance is the length of the marble's path from A to C. Displacement is the change in the marble's position from point A to C, influenced by the direction of the marble's motion.*

*L: What units and measuring instruments measure distance and displacement?*

*S: Hmm (student thinks and reviews the supporting information on the front page of the SW). Maybe use a ruler, ma'am. The unit is centimeters. L: Do you measure the distance and displacement between the marbles?*

*S: Yes, that's right, ma'am. That means I use a ruler or tape measure to measure longer distances. The units are meters.*

*L: Try shooting a marble eastward and stopping it southward. Can you determine its speed and velocity? Can you explain?*

*S: Hmm (thinks for a moment), I've measured distance and displacement, ma'am.*

*L: Besides that, can you measure anything else while the marble moves?*

*S: Yes, ma'am, time.*

*L: What can be formulated from these two quantities?*

*S: Hmm (thinks and reviews the supporting information). Yes, ma'am, we can determine velocity and speed.*

*L: What's the difference between the two?*

*S: Speed is a measure of distance over time, where direction is unrelated. Velocity is the change in time that is affected by the direction of the marble's motion.*

*L: Can you group the quantities for distance, displacement, velocity, and speed?*

*S: Hmm, I can, ma'am. Quantities that only have a value, such as distance and speed, are called scalar quantities (while reviewing the supporting information). Velocity and displacement are vector quantities.*

*L: Record the data you can see from the movement of the marbles, moving in the same direction every 2 seconds for three trials. What is the average velocity?*

*S: (The student conducts the experiment and records the measurements while thinking). Calculating the average velocity means the total of all three parts, ma'am.*

*L: What if I want to get information on the velocity at 4 seconds?*

*S: Hmm, that means the data taken during the second trial, ma'am.*

*L: Can you conclude this marble game's average and instantaneous velocity?*

*S: Yes, ma'am. Average velocity is the total velocity of all the marbles moving during the experiment. Instantaneous velocity is the velocity of the marbles moving at a specific time.*

*L: From the experimental data, can you calculate the average acceleration and acceleration at any given time?*

*S: Yes, ma'am, while calculating.*

*L: Is it possible for the marbles to slow down? How can you explain it?*

*S: Yes, ma'am. When the marbles are about to stop, their speed slows down. This means this is deceleration, ma'am, where the marbles' speed slows down.*

*L: Rewrite the formula, scientific notation, and units you learned from your marble playing experience!*

*S: Okay, ma'am, I'll write it all down.*

### 3.2.2 Students with Average Academic Ability

Students with average academic ability are able to understand the instructions and questions listed on the SW quite well. After understanding the instructions, they immediately begin playing marbles according to the procedures described. In carrying out the activity, students in this category demonstrate a careful and meticulous attitude. They take the time to think before taking measurements or recording data, and try to ensure that each step is carried out according to the instructions in the worksheet. The data collection process is carried out thoroughly, although it takes relatively longer than for students with high abilities. This careful attitude shows a reflective effort to understand the relationship between the observed phenomena and the kinematics concepts being studied. Thus, students with average abilities demonstrate a systematic

and understanding-oriented pattern of thinking, although they still need guidance in connecting empirical observations with formal representations of physics concepts. The following is an excerpt from an interview between a lecturer (L) and a student (S).

*L: How do you determine distance and displacement in this marble game?*

*S: Conceptually, distance is the length of the path traveled by an object (a marble). So, the distance I found here is when I shot marble A with another marble, and marble A moved this far to point C. Displacement, on the other hand, is the change in the marble's initial and final positions. Here, displacement is the same as distance, but it has a direction of motion, ma'am.*

*L: How do you determine speed and velocity?*

*S: We can find other velocities by calculating the distance and time the marble travels. If we calculate the displacement of the marble from its initial to final position and the time it takes to travel, we can estimate its velocity, ma'am.*

*L: What about the instantaneous velocity and average velocity?*

*S: Instantaneous velocity is the marble's speed at a specific time. For example, I recorded data from my measurements for the first 2 seconds. The instantaneous velocity at 2 seconds is the displacement divided by the time it takes. The average velocity is obtained by combining all the instantaneous velocities across the many trials.*

*L: What about acceleration and deceleration?*

*S: Acceleration is the rate of change of speed over time. This means that the velocity is positive, meaning it's increasing. Deceleration is negative, meaning the velocity is decreasing.*

*L: Can you group the quantities you found in the marbles game above? Can you create a scientific formula with its standard units?*

*S: Yes, ma'am. Students can write it down.*

### 3.2.3 Students with High Academic Ability

Students with high academic abilities demonstrate good cognitive competence in understanding the instructions and questions contained in the SW. They are able to interpret each stage of the activity quickly and accurately, and show great enthusiasm in carrying out the entire series of learning activities. Students in this category fill out the

worksheet systematically, make careful observations, and carry out field experiments with a relatively high degree of independence. During the activity, students were active and showed great interest in the hands-on learning process. The marble game activity in the field provided them with the opportunity to apply physics concepts in a contextual manner while verifying their prior theoretical understanding. This enthusiasm also reflected the emergence of intrinsic motivation in learning, where students not only focused on the end result but also enjoyed the process of discovering and exploring kinematic concepts through concrete activities. The following is an excerpt from an interview between a lecturer (L) and a student (S).

*L: How did you determine the acceleration of this marble?*

*S: First, I found the marble's displacement from its initial to final position. Then, I recorded the time it took to move between the two positions. After that, I calculated the marble's velocity using the solution-in-time calculation. The acceleration value can be obtained since acceleration is the first derivative of velocity with respect to time or the second derivative of displacement with respect to time.*

*L: How would you explain the difference between acceleration and deceleration in this marble game?*

*S: Acceleration and deceleration are similar phenomena affected by changes in velocity. If the marble moves at an increasing speed over time, it is called an accelerating marble. Conversely, if its velocity decreases over time, it is decelerating.*

### 3.3 Retrospective analysis

Based on the results of the teaching experiments conducted, two major revisions to the initial HLT design were identified. These revisions were made to align the learning flow with students' actual thinking processes so that the activity stages could proceed more effectively and progressively. In the revised HLT, the sequence of learning activities is arranged from simple questions to higher levels of complexity. This gradual approach is intended to adapt to students' cognitive dynamics, so that the designed iceberg model can function optimally in helping students discover, reconstruct, and develop their understanding of kinematics concepts. In addition, the lecturer plays an active role in anticipating student learning difficulties through the use of planned probing questions.

These questions are designed to stimulate student reflection on their observations and encourage them to engage in scientific reasoning. Examples of questions asked include: "Did you find the distance between the marbles after they were fired?", "Reconsider the movement of the marbles from point A to point C. Can you indicate their displacement?", "Are distance and displacement the same thing?", and "If a marble is fired in a semicircular path and stops exactly at the starting point, is its motion zero? Explain." This type of reflective questioning helps students identify the conceptual distinction between distance and displacement and understand the meaning of direction in the context of motion.

In the initial measurement phase, students were asked to measure the velocity of a marble every 0.5 seconds for two minutes. However, observations showed that this procedure was difficult to implement in practice. The very short observation time made it difficult for students to maintain accuracy between when the marble began moving and when they began recording on the stopwatch. Furthermore, stopping the stopwatch every 0.5 seconds to record the distance traveled proved inefficient and resulted in inaccurate measurements, especially when done manually without precise digital tools. Based on these findings, the measurement instructions on the worksheet were revised to be more realistic and appropriate for field conditions. In the revised HLT, students were asked to record the movement of a marble moving in the same direction every two seconds for three trials, then calculate the average velocity based on these observations. This revision not only improved the technical feasibility of the implementation but also allowed students to focus on the conceptual understanding of the relationship between distance, time, and velocity without being overwhelmed by the technical details of measurement. Thus, the results of this retrospective analysis indicate that the HLT revision process is adaptive to students' needs and abilities, and is oriented towards achieving deeper conceptual understanding through contextual learning based on real activities.

#### **4 DISCUSSION**

The results of this study provide a comprehensive picture of how students understand kinematic quantities through the application of the HLT, which is designed to accommodate students' thinking processes in discovering and reconstructing concepts. In the context of physics, kinematics essentially studies changes in a quantity over time,

such as the relationship between position, velocity, and acceleration, which requires a deep understanding of the meaning of quantities and their accompanying units (Bottema & Roth, 1990; Koetsier, 2024; Mueller, 2025). Therefore, students' conceptual understanding is not only determined by their ability to use formulas (Caccamo & Serpe, 2023), but also by how they interpret the relationships between quantities in a real-world time and space framework (Bollen et al., 2016; Rane, 2017; Taqwa et al., 2022).

The learning design provided through the application of HLT based on traditional marbles proved to be effective in helping students rediscover kinematic concepts and build more meaningful understanding. This learning process, integrated with the local cultural context, allows students to interpret their empirical experiences scientifically and relate them to formal physics concepts (Festiyed et al., 2024; Khery et al., 2025; Sari et al., 2024). These results are in line with the findings of Sarama and Clements (2019), who stated that learning trajectories can gradually improve students' conceptual understanding through structured activities.

Furthermore, the results of this study confirm the importance of contextual learning in overcoming difficulties in understanding abstract physics concepts. Guffey and Slater (2020) emphasize that learning processes linked to real contexts can help reduce misconceptions and strengthen the construction of scientific meaning. In this case, the use of traditional marbles as a learning context provides an authentic experience that is easily understood by students because it is rooted in cultural practices that are familiar in everyday life (Damayanti & Kuswanto, 2021; Sangila et al., 2022).

Gravemeijer and Terwel (2000) view also supports this approach, emphasizing that students' knowledge develops dynamically during the process of conceptual discovery facilitated through meaningful activities. Through exploratory activities such as marbles games, students have the opportunity to utilize their prior knowledge and adapt it to new scientific understandings, thereby creating a constructive and reflective learning process (Kamid et al., 2022; Kreinsen, 2024).

Theoretically, the results of this study can be explained through two main foundations in educational psychology. First, Piaget's theory emphasizes that individuals construct their knowledge through a process of adaptation and assimilation of new experiences (Piaget, 1976). In this context, marbles serve as a concrete experience that allows students to assimilate physics concepts through observation and measurement activities. Second, Vygotsky's theory highlights the importance of social and cultural

contexts in the learning process (Vygotsky & Cole, 1978). Through social interaction and locally-based cultural activities such as marbles games, students can collaboratively construct new meanings and strengthen their conceptual understanding.

The findings of this study also indicate that prospective elementary school teachers still hold a number of misconceptions related to kinematic concepts that originate from their previous learning experiences. These misconceptions, for example, in distinguishing distance from displacement, or velocity from speed, can be traced to learning habits that emphasize mathematical procedures over conceptual understanding. However, through the application of HLT that departs from a context familiar to student -- namely marbles -- these misconceptions can be minimized.

This research also provides an empirical model of how culture-based activities can be used as a means of exploring abstract physics concepts, thus offering a new alternative in the design of ethnoscience-based physics learning. This research also serves as a bridge between science and the local cultural context. This study enriches knowledge about how contextual learning design can support prospective teachers' conceptual understanding of basic physics. The results provide empirical evidence that the use of traditional game contexts can bridge the transition from concrete experiences to formal understanding of kinematic quantities.

Overall, the results of this study show that the developed Hypothetical Learning Trajectory (HLT) design is capable of internalizing physics concepts in a more meaningful, contextual, and relevant way to the daily lives of students. By linking scientific knowledge and the local cultural context, students not only understand physics concepts cognitively, but also appreciate the underlying cultural values and social experiences. Therefore, the application of traditional game-based HLT can be an effective strategy in the development of local instructional theory that harmoniously integrates science, culture, and pedagogy.

## 5 CONCLUSION

This study shows that the application of HLT based on traditional marbles is effective in facilitating the formation and strengthening of students' conceptual understanding of kinematic quantities. Through a structured learning design from the concrete to the abstract stage, students are able to rediscover, reconstruct, and relate

kinematic concepts -- such as position, distance, displacement, velocity, speed, acceleration, and deceleration -- to real phenomena that they experience directly. The HLT model developed in this study successfully accommodates students' thinking processes by integrating local cultural elements into the physics learning context.

Marbles, as a familiar cultural activity, have proven to be a conceptual bridge between empirical experience and scientific understanding. Through these exploratory activities, students not only learn physics formulas and symbols procedurally, but also internalize the physical meaning of each quantity through observation, reflection, and guided discussion. In addition, the results of the study confirm that pedagogical strategies based on probing questions and scaffolding play an important role in stimulating critical thinking skills and helping students overcome preconceived misconceptions.

The reflective question and answer process conducted by lecturers encourages students to review their understanding, construct scientific arguments, and correct conceptual errors independently. Theoretically, this study enriches the development of local instructional theory in science education by emphasizing the importance of integrating local cultural contexts and scientific conceptual structures. Practically, the findings of this study have positive implications for lecturers and prospective elementary school teachers in designing physics lessons that are more meaningful, contextual, and relevant to the daily lives of students. Thus, it can be concluded that the application of the marble-based HLT not only improves students' conceptual understanding of kinematic quantities but also fosters reflective, collaborative, and contextual thinking skills that are essential in 21st-century science learning.

As a follow-up to the findings of this study, several directions for future research can be considered to strengthen and expand the contribution of this study. First, similar studies can involve a more diverse group of participants, both in terms of academic ability and cultural background, to obtain a more comprehensive picture of the effectiveness of Hypothetical Learning Trajectory (HLT) in the context of kinematics learning. Second, the development of HLT can be expanded to other physics concepts, such as dynamics or circular motion, to evaluate the consistency and transferability of learning designs based on traditional game contexts. Third, further research can utilize more in-depth thinking process analysis methods, such as learning analytics or video-based observation, to identify in more detail the stages of concept construction experienced by students. Fourth, exploring the integration of technology -- such as digital simulation or augmented reality

-- with traditional game contexts also has the potential to enrich the learning experience while improving the traceability of the learning process. Thus, these follow-up studies are expected to strengthen the validity of the findings, expand the application of culture-based contextual learning design, and make a greater contribution to the development of physics learning theory in the future.

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### ETHICAL APPROVAL

This study involving prospective elementary school teachers was conducted in accordance with national and institutional ethical standards. Prior to data collection, approval was obtained from the university. Participation was completely voluntary. To maintain confidentiality, student identities were anonymized, and no personal data was collected or disclosed. All procedures adhered to the principles of the Declaration of Helsinki, research ethics, and were in accordance with the journal's policy on research involving human subjects..

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#### **Authors' Contribution**

Both authors contributed equally to the development of this article.

#### **Data availability**

All datasets relevant to this study's findings are fully available within the article.

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