

Analysis of Student Learning Trajectories in Inquiry-Based Science Learning

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Abstract

This study aims to analyze student learning trajectories in the context of inquiry-based science learning, with a particular focus on how students' conceptual understanding and thinking processes develop throughout inquiry activities. Employing a qualitative research design, the study involved students participating in structured inquiry-based science learning encompassing problem orientation, question formulation, exploration, data analysis, and conclusion drawing. Data were collected through classroom observations, student worksheets, written responses, and excerpts of classroom discussions, and were analyzed using thematic analysis grounded in the learning trajectories framework. The findings reveal that inquiry-based learning generates diverse learning trajectories, including progressive conceptual trajectories, partial trajectories, and constrained trajectories, reflecting variations in students' cognitive engagement and conceptual development. The results indicate that inquiry-based learning facilitates the gradual restructuring of students' conceptual understanding and supports the development of higher-order thinking skills, although students follow different paths in achieving scientific understanding. This study contributes to science education literature by highlighting the importance of examining learning processes rather than solely learning outcomes and underscores the value of learning trajectories as an analytical lens for understanding student learning in inquiry-based science classrooms.

Keywords:

Inquiry-based science learning; Learning trajectories; Conceptual understanding

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1. INTRODUCTION

21st-century science education faces increasingly complex challenges as scientific inquiry, critical thinking, and problem-solving skills are required as key competencies for students (Mutohhari et al., 2021). Science education is no longer viewed merely as a process of transferring factual knowledge, but rather as a means of building conceptual

understanding through investigative activities that mimic the way scientists work (Jiménez-Valverde, 2025). This paradigm shift encourages a transition from a teacher-centered approach to student-centered learning, where students play an active role in formulating questions, exploring phenomena, analyzing evidence, and drawing conclusions based on scientific reasoning (Tang, 2023). However, in practice, science education still often emphasizes final results and correct answers, while students' thinking processes develop gradually, non-linearly, and are highly dependent on their learning experiences (Bao et al., 2022). Therefore, a learning approach is needed that can facilitate and map students' learning processes in a meaningful way (Vargas-Hernández & Vargas-González, 2022), so that teachers not only evaluate what students have learned, but also how that understanding is formed and developed throughout the science learning process (Darling-Hammond et al., 2024).

Inquiry-based science learning (IBSL) is a pedagogical approach that places the scientific inquiry process at the core of science learning, where students are actively involved in formulating questions, designing and conducting investigations, analyzing data, and constructing evidence-based explanations (Tisoglu et al., 2025). The main characteristics of IBSL include active student involvement, the use of open-ended questions, exploration of authentic phenomena, and reflection on the process and results of the investigation (Dian, 2024). Through this approach, students not only develop a deeper conceptual understanding, but also scientific process skills such as observation, inference, causal reasoning, and scientific argumentation. However, the implementation of inquiry learning presents significant challenges, especially for teachers in monitoring and understanding student learning progress, which is dynamic and diverse (Chen & Chen, 2025). The inquiry process often results in different paths of understanding among students, making it difficult to identify solely through final assessment (Alharbi, 2023). This condition emphasizes the need for an analytical framework that is capable of capturing the continuous learning process of students, so that inquiry-based learning can be implemented effectively and adaptively in accordance with students' learning needs.

Inquiry-based science learning inherently results in diverse learning trajectories among students, as each individual brings different prior knowledge, thinking strategies, and ways of interacting with inquiry activities (Morris, 2025). In the process of formulating questions, conducting investigations, and interpreting evidence, students may follow paths of understanding that are not uniform, either in speed or in depth of conceptual development (Lindsey et al., 2023). Therefore, analyzing learning trajectories is crucial to understanding how students respond to each stage of inquiry activities, including how they construct, revise, or even maintain misconceptions (Confrey & Shah, 2021). Through learning path mapping, teachers and researchers can identify patterns in student understanding and critical points that require pedagogical support (Knight & Sullivan, 2022). The role of teachers in this context is not only as facilitators of inquiry, but also as observers and pedagogical decision-makers who adjust learning interventions based on students' learning trajectories. Thus, the integration of inquiry-based learning and learning trajectory analysis enables science learning that is more adaptive, responsive, and oriented towards the learning process of students.

Although inquiry-based science learning has been extensively researched, most studies still focus on measuring learning outcomes, such as conceptual achievement or test scores, rather than conducting in-depth analysis of the learning process of students (Mediana et al., 2025). An excessive focus on learning outcomes often overlooks how students' understanding is formed, developed, and changed during their involvement in inquiry activities. In addition, empirical studies that systematically analyze student learning trajectories in the context of inquiry-based science learning are still relatively limited, especially research that maps students' thinking stages continuously. As a result, variations in students' learning trajectories in terms of reasoning strategies, the emergence of misconceptions, and conceptual shifts are not yet fully understood (Clements & Sarama, 2025). This limitation indicates a significant scientific gap, namely the need for research focused on analyzing student learning trajectories to reveal the dynamics of the learning process in inquiry-based science learning.

Based on this research gap, this study aims to analyze students' learning trajectories in inquiry-based science learning, focusing on how students' conceptual understanding develops throughout their involvement in inquiry activities. Theoretically, this study is expected to enrich the science education literature by providing empirical evidence on the role of learning trajectories as an analytical framework for understanding student learning processes more deeply, particularly in the context of inquiry-based science learning. From a practical perspective, the findings of this study are expected to provide insights for teachers in designing and implementing more adaptive inquiry learning, by adjusting pedagogical strategies, activities, and interventions based on students' learning trajectories, so that science learning is not only oriented towards the final outcome, but also towards the quality and meaningfulness of the students' learning process.

2. METHOD

This study uses a qualitative approach with an exploratory-descriptive study design, which aims to analyze students' learning trajectories in inquiry-based science learning. This approach was chosen because learning trajectories represent students' thinking processes and conceptual development, which are dynamic, contextual, and cannot be fully explained through quantitative measurements alone.

The research subjects were students who participated in inquiry-based science learning in a specific learning unit/topic. The subjects were selected purposively, taking into account the students' active involvement in each stage of inquiry, from formulating questions to exploration and conclusion. Data were collected from various sources to comprehensively capture the students' learning process, including student worksheets (LKS/LKPD), inquiry assignment results, class discussion recordings, observations of the learning process, and semi-structured interviews with students and teachers. The use of various data sources aimed to increase the depth of analysis and credibility of the findings.

Data analysis was conducted in stages using a thematic analysis and learning trajectory analysis approach, which included identifying learning objectives, mapping students' stages of understanding, and tracing conceptual changes that occurred during the inquiry process. Data were analyzed through an open coding process to identify patterns in student responses, followed by axial coding to group the stages of understanding that formed

learning trajectories. The validity of the research was maintained through data and method triangulation, discussions among researchers (peer debriefing), and checking the consistency of interpretations against empirical evidence. With this approach, the research is expected to provide an in-depth and systematic description of students' learning trajectories in inquiry-based science learning.

3. RESULTS AND DISCUSSION

3.1. Results

Overview of the Inquiry-Based Science Learning Process

Inquiry-based science learning in this study is designed to facilitate students' thinking processes gradually through a series of activities that place students at the center of learning. The inquiry process is carried out systematically, starting from the introduction of contextual problems to the formulation of data-based conclusions. Each stage of inquiry provides students with the opportunity to observe phenomena, formulate questions, explore, analyze information, and actively build conceptual understanding. Thus, learning is not only oriented towards achieving final learning outcomes, but also towards the dynamics of the students' learning process during the inquiry activities.

Table 1. Stages of Inquiry-Based Science Learning and Student Activities

Inquiry Stage	Description of Learning Activities	Main Student Activities	Indications of the Thinking Process
Problem Orientation	Presentation of contextual scientific phenomena through visual media or demonstrations	Observe, express initial opinions, relate to everyday experiences	Activation of prior knowledge and emergence of curiosity
Formulation of Questions	Facilitate the development of investigative questions	Formulating and discussing research questions	The shift from descriptive to causal thinking
Exploration	Conducting experiments and collecting data	Conduct experiments, record results, make predictions	Evidence-based reasoning and hypothesis testing
Data Analysis	Processing and interpretation of exploration data	Compare results, discuss, relate to concepts	Strengthening analytical and argumentative reasoning
Conclusion	Preparation of conclusions and reflections on learning	Formulating conclusions and communicating results	Integration of concepts and generalization of understanding

Based on Table 1, each stage of inquiry contributes differently but complementarily to shaping students' continuous learning process. The problem orientation and question formulation stages play an important role in building students' cognitive readiness, while also revealing initial response variations that reflect differences in thinking patterns among students. Furthermore, the exploration and data analysis stages provide space for students to develop conceptual understanding through direct interaction with data and observed phenomena. In the conclusion stage, students demonstrate their ability to integrate information and draw evidence-based generalizations, which marks the development of scientific reasoning. These findings show that the implementation of inquiry-based science learning is not only in line with the principles of 21st-century science learning but also effective in revealing and tracing students' learning trajectories more clearly during the learning process.

Identifying Student Learning Trajectory Patterns

Analysis of the inquiry learning process shows that students do not follow a uniform learning trajectory. During the inquiry stage, there are variations in learning trajectories that reflect differences in how students construct conceptual understanding, interpret data, and draw scientific conclusions. These variations are evident in students' responses at each stage of inquiry, from formulating questions to drawing conclusions. Based on a qualitative analysis of student activities, written answers, and discussions, student learning trajectories can be classified into several main patterns that reflect different levels of cognitive engagement and conceptual understanding development.

Table 2. Classification of Student Learning Trajectories in Inquiry-Based Science Learning

Learning Journey Pattern	Key Characteristics	Student Responses During Inquiry	Indications of Cognitive Involvement
Progressive Conceptual Path	Understanding develops gradually and consistently	Able to formulate meaningful questions, relate data to concepts, and draw logical conclusions	High (analytical, reflective, and argumentative)
Partial Conceptual Path	Understanding is developing but not fully integrated	Active in the exploration stage, but having difficulty connecting the results to scientific concepts	Moderate (procedurally dominant, limited to interpretation)
Obstructed Path	Conceptual understanding did not develop significantly	Tends to follow instructions without deep reflection, difficulty drawing conclusions	Low (descriptive and reactive)

In addition to general classifications, differences in learning trajectories are also evident in students' response patterns at each stage of inquiry. To clarify these dynamics, the following table presents the characteristics of student learning trajectories in each phase of inquiry-based learning.

Table 3. Characteristics of Student Responses at Each Stage of Inquiry Based on Learning Trajectories

Inquiry Stage	Progressive Path	Partial Trajectory	Obstructed Path
Formulation of Questions	Investigative and causal questions	Descriptive and limited questions	Difficulty formulating questions
Exploration	Directed and reflective exploration	Procedural exploration	Mechanical exploration
Data Analysis	Evidence-based interpretation and concepts	Interpretation limited to results	Minimal analysis
Conclusion	Integrated and argumentative conclusions	Partial conclusion	Inconsistent conclusions

These findings indicate that variations in learning trajectories are a logical consequence of the open nature of inquiry-based science learning, which provides space for students to construct knowledge through different cognitive pathways. Students with progressive conceptual trajectories demonstrate higher cognitive engagement, characterized by reflective, analytical, and argumentative abilities throughout the inquiry process. Conversely, partial and inhibited trajectories indicate limitations in integrating exploratory experiences with conceptual understanding, even though students remain actively engaged at certain levels. These findings confirm that inquiry-based learning not only produces variations in learning outcomes but also reveals the complex dynamics of students' thinking

processes, making the analysis of learning trajectories important for understanding how and why students learn differently in the context of inquiry-based science learning.

Stages of Development of Students' Conceptual Understanding

Analysis of student learning artifacts during inquiry-based science learning shows that students' conceptual understanding develops through relatively gradual stages, rather than instantly. This development is evident from changes in the way students explain phenomena, interpret exploration data, and construct scientific arguments. The findings indicate three main stages of conceptual understanding, namely initial understanding, conceptual transition phase, and scientific understanding. These stages are not always linear for each student, but reflect the conceptual development trajectory that commonly emerges during the inquiry process.

1. Initial Understanding

In the early stages of learning, students generally bring intuitive understanding or initial conceptions that are descriptive and based on everyday experiences. This understanding is often not supported by accurate scientific concepts and still contains misconceptions. This can be seen when students respond to problem-oriented questions with superficial explanations. For example, one of the students' answers on the initial worksheet states:

"In my opinion, this happened because the object changed on its own when heated."

These answers show that students have observed the phenomenon, but are not yet able to relate it to relevant scientific concepts. At this stage, inquiry serves as a catalyst for cognitive conflict by bringing together students' initial understanding with phenomena or data that cannot be fully explained by their initial conceptions.

2. Conceptual Transition

The conceptual transition stage is marked by the emergence of students' attempts to revise their initial understanding through exploration and data analysis. Students begin to use scientific terms, although their application is not yet fully consistent. In this phase, group discussions and data analysis activities play an important role in encouraging the restructuring of understanding. The following excerpts from student discussions illustrate this transition phase:

"At first I thought it was just a change in shape, but after looking at the data, it seems to be related to the heat energy supplied."

This statement indicates a shift from intuitive explanations to concept-based understanding, although it still needs reinforcement. Inquiry-based learning at this stage facilitates students to test their initial ideas, compare observation results, and begin to build more logical cause-and-effect relationships.

3. Scientific Understanding

At a more scientific level of understanding, students are able to integrate the results of their exploration, empirical data, and scientific concepts in a more coherent manner. Students' understanding is not only descriptive, but also argumentative and evidence-based. This can be seen from the students' answers in the conclusion section of the worksheet. For example, one of the students' conclusions states:

"Based on the results of the experiment and the data obtained, the changes that occurred were influenced by heat energy, which caused changes in the properties of substances in accordance with the concepts studied."

This answer shows that students have achieved a more stable and scientific conceptual understanding, where concepts are not only used as terms, but as tools for thinking to explain phenomena. Overall, these findings indicate that inquiry-based science learning plays an important role in facilitating the restructuring of students' conceptual understanding through gradual and meaningful stages. The inquiry process allows students to reflect on their initial understanding, experience cognitive conflict, and actively construct scientific concepts through interaction with data and discussion. The stages of development found are in line with the learning trajectories framework, which emphasizes that students' understanding develops through progressive trajectories, and is consistent with the constructivist perspective that views learning as an active process of constructing knowledge, rather than simply receiving information.

The Dynamics of Student Thinking During Inquiry Activities

Analysis of student activities during inquiry-based science learning shows that students' thinking processes undergo clear dynamics and develop as the inquiry stages progress. These changes are not only evident in the quality of the final answers, but especially in the way students formulate questions, make predictions, interpret data, and draw conclusions. This dynamic reflects a shift from simple thinking patterns to more complex and reflective cognitive strategies, although the level of development varies among students.

In the early stages of inquiry, most students tend to formulate questions that are descriptive and limited to what is immediately apparent. The questions asked still focus on "what happened" and do not yet explore cause-and-effect relationships. However, as exploration and data collection activities progress, students' questions begin to shift toward more analytical and predictive ones. This change can be seen, for example, when students begin to ask questions such as:

If this variable is changed, will the result remain the same?

This question shows that students are no longer merely observing phenomena, but are beginning to anticipate possible outcomes and relationships between variables. At this stage, inquiry encourages students to think hypothetically and develop predictive thinking skills, which is one indicator of higher-order thinking skills.

In the process of making predictions, differences in cognitive strategies were found among students. Some students based their predictions on personal experience or intuition, while others began to use preliminary data or the results of group discussions as the basis for

their arguments. These differences in strategy show that inquiry-based learning provides space for variations in students' ways of thinking, in accordance with their respective levels of understanding and cognitive experience.

When drawing conclusions, students with more progressive learning trajectories tend to explicitly link empirical findings with scientific concepts. Conversely, students with partial or stunted learning trajectories still show difficulty in synthesizing data into coherent conclusions. This confirms that the quality of students' thinking processes is not always directly reflected in the final results, but needs to be understood through an analysis of the inquiry process they undergo. These findings indicate that inquiry-based science learning plays a significant role in developing higher-order thinking skills, such as analysis, evaluation, and reflection. Inquiry requires students not only to find answers, but also to explain how and why a conclusion can be drawn. Thus, the focus of learning shifts from the final result to the underlying thought process.

In addition, the results of this study emphasize the importance of monitoring the dynamics of students' thinking processes during inquiry. Correct final answers do not always reflect deep conceptual understanding, while incorrect answers can indicate significant developments in thinking. Therefore, analyzing learning trajectories and students' thinking processes is crucial for teachers in designing adaptive learning interventions that are responsive to students' learning needs.

3.2. Discussion

This study aims to understand how students' learning trajectories are formed and developed in the context of inquiry-based science learning, with a focus on students' thinking processes and conceptual understanding development. The main findings of the study indicate that inquiry does not produce a uniform learning path, but rather gives rise to diverse conceptual development paths that reflect differences in students' cognitive engagement and thinking strategies (De Jong et al., 2025). This indicates that learning trajectories are dynamic constructs influenced by the interaction between inquiry activities, student characteristics, and open learning contexts (Payadnya et al., 2023).

Conceptually, the results of this study confirm that inquiry-based learning functions as a mechanism that facilitates the gradual restructuring of students' understanding (Li et al., 2025). The inquiry process encourages students to move from intuitive initial understanding to more scientific understanding through a cycle of questioning, exploration, and reflection (Schwartz et al., 2023). The identified differences in learning trajectories can be understood as a consequence of the constructivist approach, in which students construct knowledge based on their experiences and cognitive frameworks. Thus, learning trajectories not only describe the ideal learning sequence, but also reflect the reality of students' non-linear learning processes.

From a cognitive perspective, the dynamics of students' thinking processes during inquiry show that the quality of science learning cannot be reduced to the achievement of final results alone. Inquiry provides space for the development of higher-order thinking skills, such as analytical, hypothetical, and reflective thinking, although the level of emergence varies among students (Antonio & Prudente, 2023). These findings provide a scientific explanation as to why some students are able to achieve a more integrated

conceptual understanding, while others are still in a transitional stage or experience conceptual obstacles. These differences do not necessarily indicate learning failure, but rather reflect ongoing stages of cognitive development.

Compared to previous studies that focused more on learning outcomes, this study broadens our understanding of science learning by highlighting the importance of analyzing students' learning processes and trajectories. The results of this study are in line with the view that inquiry-based learning enriches students' cognitive experiences, but also emphasize that the effectiveness of inquiry depends heavily on how students' learning processes are monitored and interpreted. The differences in learning trajectories found indicate that the inquiry approach does not automatically produce deep scientific understanding, but requires pedagogical support that is sensitive to students' cognitive development.

Overall, the findings of this study make an important contribution to understanding the relationship between inquiry-based science learning and learning trajectories. These results address the research objectives by demonstrating that learning trajectory analysis is an effective conceptual tool for revealing how students think, learn, and develop during inquiry. Thus, this study confirms that the success of inquiry-based science learning is determined not only by the design of activities, but also by the ability of educators to read, interpret, and respond to the dynamics of students' learning trajectories in a pedagogical and sustainable manner.

4. CONCLUSION

This study concludes that inquiry-based science learning produces diverse and dynamic learning trajectories among students, reflecting differences in their thinking processes and conceptual understanding during learning. Inquiry serves as a pedagogical framework that enables students to move from initial understanding to more scientific understanding through the stages of questioning, exploration, analysis, and reflection, even though the development path is not always linear. These findings confirm that analyzing learning trajectories provides a deeper understanding of the quality of science learning than simply measuring final outcomes, and highlights the importance of the teacher's role in monitoring and responding to the dynamics of students' thinking processes so that inquiry-based learning can optimally support conceptual development.

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