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Designing Semantic Tutoring Maps for Enhancing Peer Learning through Lesson Preparation

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Abstract

Advancements in Natural Language Processing technologies present significant opportunities to enhance student learning through peer tutoring. While extensive research highlights the effectiveness of peer tutoring in learning science, there is a notable lack of studies addressing the lesson preparation stage of peer tutoring. This study utilizes Semantic Web technologies to organize tutoring maps, aiming to develop an innovative educational artifact that fills this research gap. Employing a design-based research methodology, we begin with a comprehensive literature review on the application of semantic technologies in education and peer tutoring preparation. Following this, we present a tutoring map application that utilizes a semantic database to organize and store tutoring lesson plans through Resource Description Framework (RDF) technology. Additionally, we implement querying and feedback for assessing lesson plan quality using SPARQL Protocol and RDF Query Language (SPARQL) technology. This paper outlines the theoretical framework and design rationale that enhance student tutors' learning through structured tutoring preparation, which fosters cognitive and metacognitive skills, encourages critical questioning, anticipates responses, and facilitates guidance for incorrect answers. We conclude with recommendations for educational researchers and practitioners, emphasizing future empirical studies on peer tutoring within scientific domains to validate and adapt this design, ultimately promoting peer-assisted learning and collective knowledge building.

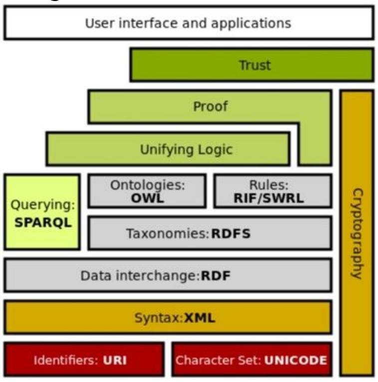
Keywords: semantic technology, peer tutor, prepare for tutoring, tutor training

1. Introduction

This study explores the concept of learning through tutoring, often referred to as learning by teaching. Peer tutoring is a collaborative learning strategy where students take on the roles of tutors and tutees, guiding one another within groups (Falchikov, 2003; Topping, 2005). In this context, one or more students act as tutors, while their peers receive support as tutees (McLuckie & Topping, 2004). Teachers oversee this process to ensure its effectiveness. Extensive research has demonstrated that peer teaching is an effective educational approach, as it deepens the tutors' understanding of the material by necessitating clear explanations and interactions with others (e.g., Abdelkarim & Abuiyada, 2016; Ullah et al., 2020; Choi et al., 2021).

In this study, we leverage advancements in artificial intelligence, specifically natural language processing technologies, to enhance the tutoring experience. The semantic web standards developed by the World Wide Web Consortium (W3C) are central to our approach, as they enable data on the internet to be both machine-readable and human-readable. Figure 1 (W3C, 2024) illustrates the family of semantic technologies, with the upper layer representing user interfaces that facilitate human interaction with semantic web applications. We employ foundational technologies -- Resource Description Framework (RDF), SPARQL Protocol and RDF Query Language (SPARQL) -- to develop our tutoring application. RDF provides a framework for graphically representing resource information through triple statements, serving as a standard model for data interchange on the web by using "subject-predicate-object" triples to define resources. SPARQL, as a query language, enables the effective retrieval of data from RDF-based resources, making it an essential component of semantic applications.

Figure 1: Semantic Web Stack



Source: https://www.w3.org/standards/semanticweb/

In the field of learning and teaching, semantic technologies have been applied in various innovative ways, as highlighted by the following research studies.

Development of Learning Tools: Isotani et al. (2013) created an intelligent authoring tool for representing knowledge related to collaboration, demonstrating its effectiveness in designing teaching activities for novice teachers. Leo et al. (2019) implemented an automatic system for generating multiple-choice questions and empirically evaluated its effectiveness in a medical education context. Tzoumpa and Mitropoulos (2020) provided empirical evidence supporting the enhancement of geometric thinking and learning among junior middle school students.

Recommendations for Learning Resources: Wu et al. (2020) developed a semantic description and recommendation framework for educational resources, integrating learning diagnostics and instructional reasoning rules.

Evaluation of Learning: Ali and Falakh (2020) designed a self-evaluation system, demonstrating its effectiveness and efficiency in vocational schools.

In addition to these applications, reviews and critical analyses of semantic technologies have emerged. Jensen (2019) conducted a systematic literature review that categorized the use of semantic technologies in formal education into eight areas: semantic web ontologies, educational resources, linked data, virtual learning, learning objects, assessment, services, and pedagogical tools for teachers and students.

Despite these advancements, semantic technologies have not yet been extensively utilized in peer tutoring. Therefore, this study aims to address this gap by developing a structured lesson preparation tool that leverages semantic technologies.

2. Methods

This study employs a design-based research (DBR) method to create a tutoring map artifact for lesson planning. Originating from the field of learning science (Brown, 1992), DBR is a design science approach that seeks to address complex issues at the intersection of theory and practice in educational research. The DBR process encompasses several key stages: identifying a problem and potential solutions, designing an artifact, demonstrating its application, collecting and analyzing data, engaging in iterative design, and ultimately generating new theories and frameworks to enhance our understanding of learning and teaching (Armstrong et al., 2020). This paper presents the current findings from this ongoing project, focusing on the design outcomes of the semantic tutoring map and discussing its design rationale, which is grounded in theoretical foundations.

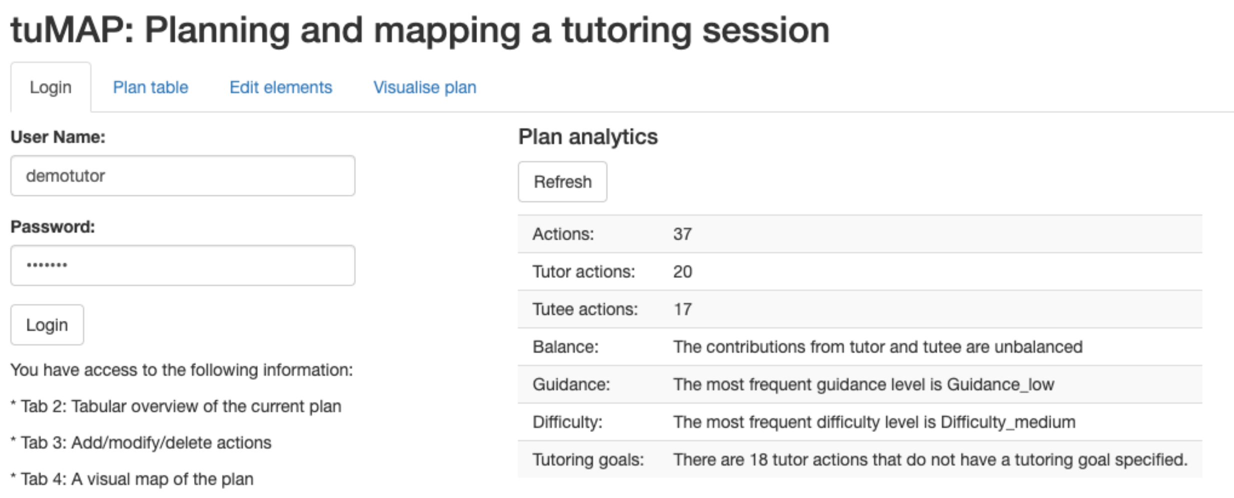
3. Results

Preparing a tutoring lesson plan can be particularly challenging for beginners, especially when navigating new content, unfamiliar pedagogical knowledge, and the integration of semantic technologies. Structured and modeled tutoring maps can assist student tutors in managing the inevitable contingencies that arise during the tutoring process, such as time management, content organization, and addressing the attitudes or emotions of participants (Milkova, 2012). This section outlines the design of the application's user interface, which is organized into four main tabs.

3.1 Tab 1: User Login

The first tab (Figure 2) presents the user login interface and includes basic analytics for the current lesson plan, such as the number of actions taken, guidance provided, difficulty levels, and missing tutoring goals.

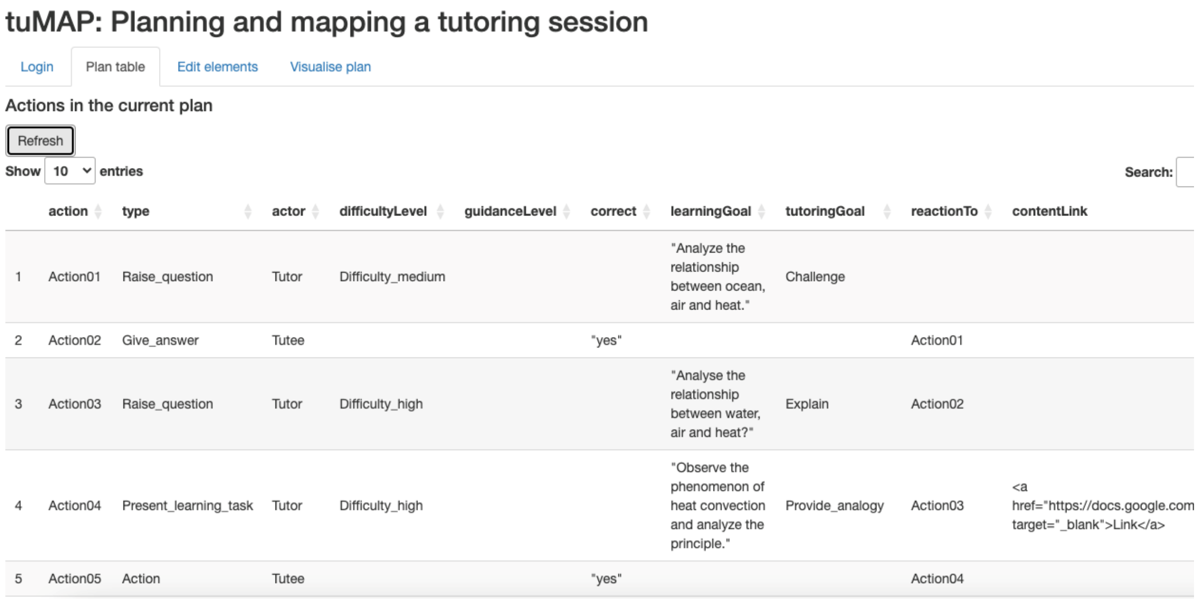
Figure 2: Login interface



3.2 Tab 2: Summary Sheet

The second tab (Figure 3) displays an automatically generated summary sheet, providing detailed information for all tutoring actions. This includes the action ID, action type, actor, difficulty level, guidance level, correctness, learning goal, tutoring goal, relationships to other actions, and content links. Users can sort the data in each column by clicking on the column headers. The interface for editing these tutoring elements is available in the following tab.

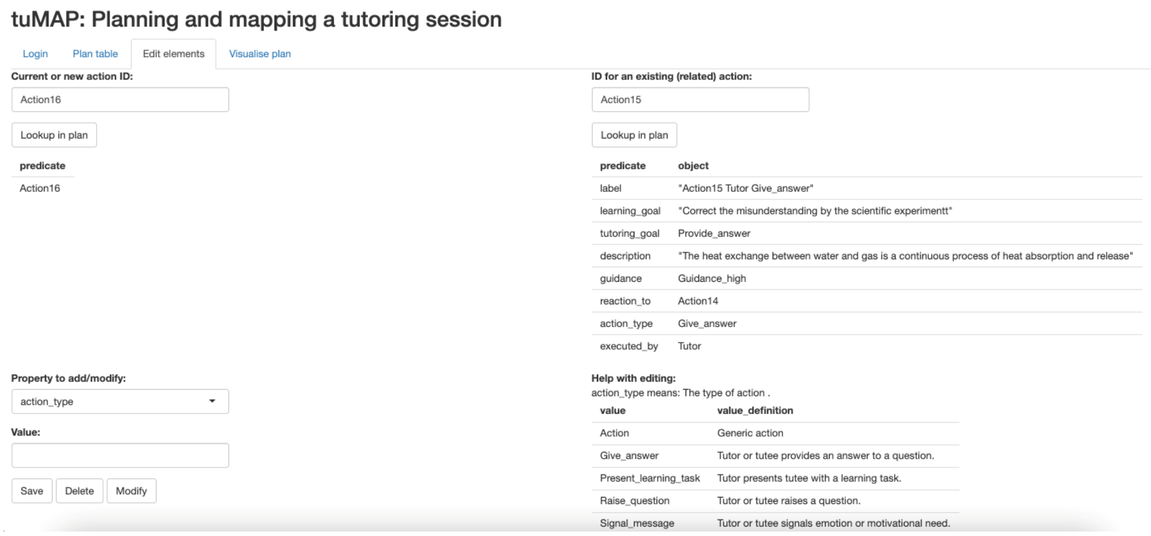
Figure 3: Summary interface



3.3 Tab 3: Lesson Plan Editing

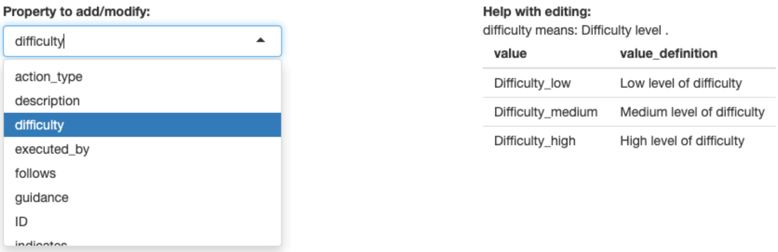
The third tab (Figure 4) functions as the primary editing interface, allowing tutors to save or modify tutoring actions within their lesson plans. On the left, users can select tutoring properties from a dropdown menu and input values for each. On the right, users can reference content from previous actions. A help section is also provided, offering explanations of each property and suggesting possible values. The action ID, displayed in the upper left corner, identifies the current action being edited, starting from "Action01" and incrementing with each new action.

Figure 4: Editing interface



The dropdown menu (Figure 5) in the lower left allows users to select action properties such as action type, action description, actor (i.e., who executes the action), difficulty level, guidance level, and more. Each property requires specific values. For example, determining whether the action type is a question or an answer or whether the difficulty level is low, medium, or high. Whenever a property or value is added, deleted, or modified, the content is automatically updated both in the table displayed in the center-left and the summary sheet on the second tab.

Figure 5: Tutoring elements



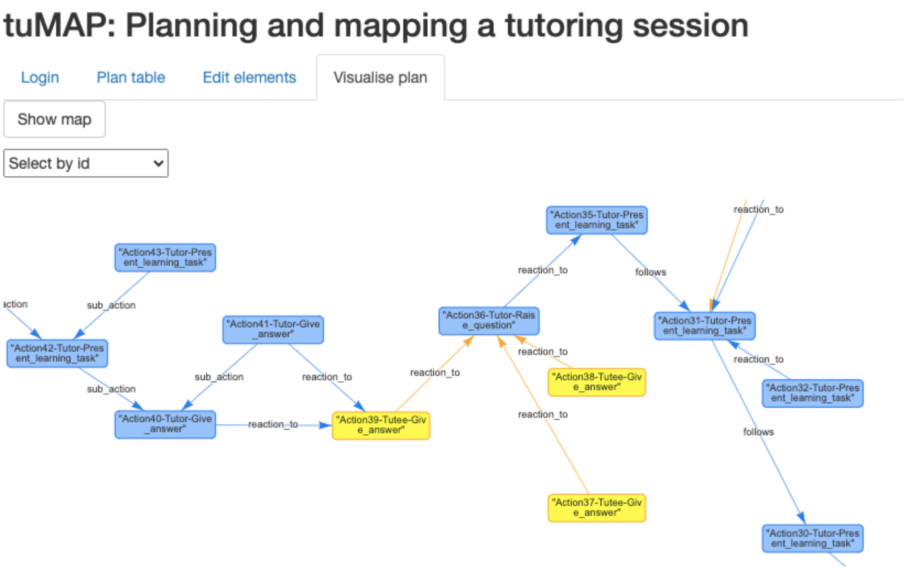
The lower right section (see Figures 4 and 5) provides editing assistance by defining the currently selected property and offering optional values for user input. This feature is designed to support novice tutors in lesson preparation. Specific support for lesson plan editing will be discussed in the next section.

The editing syntax follows the RDF format of "subject-predicate-object," where the action ID represents the subject, the property functions as the predicate, and the value is the object. Each tutoring action consists of several structured properties (predicates) with user-defined values (objects), establishing a comprehensive framework for tutoring lesson planning.

3.4 Tab 4: Visualization

The fourth and final tab (Figure 6) presents an automatically generated visual tutoring map based on the elements edited by users. Actions performed by the tutor and tutee are distinguished by two different colors. Although each action contains detailed information, the nodes are labeled only with "action_ID," "actor," and "action_type." Relationships between actions, such as "reaction_to," "follow," and "sub_action," are also displayed. This visualized graph illustrates the flow of tutoring actions, enabling users to identify gaps and assess the continuity and extensibility of reasoning chains.

Figure 6: Visualized graph

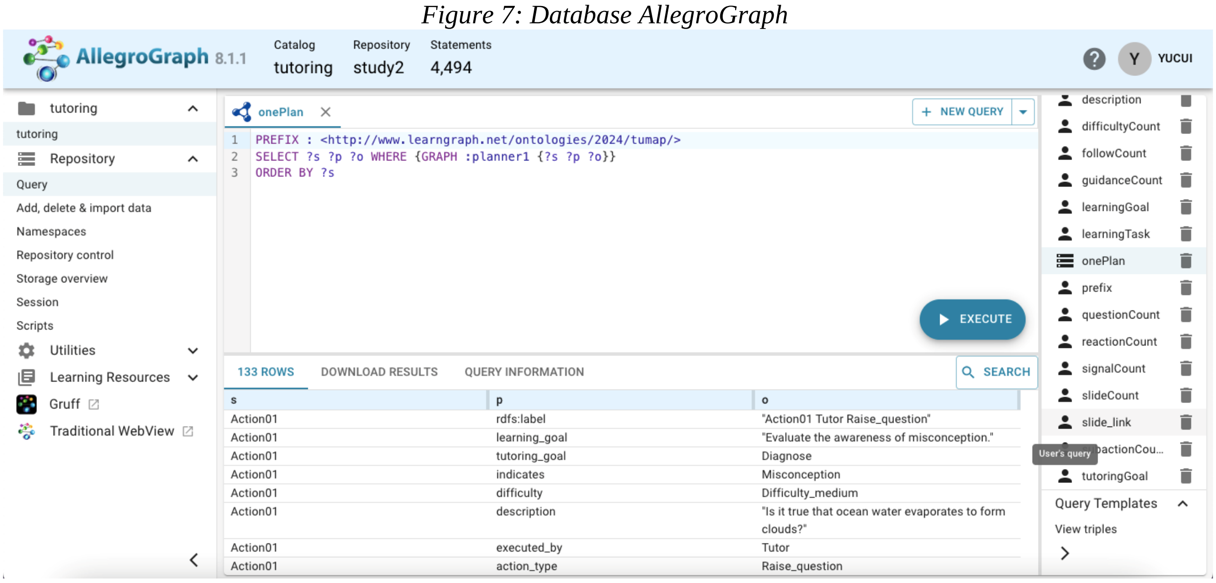


The four tabs described above make up the application's user interface. Only the third tab is editable by tutors, while the others are automatically generated for computational analysis, summarization, and visualization.

3.5 Semantic Database

Behind the scenes, the application uses a semantic database called AllegroGraph for storing and managing the graph data. AllegroGraph provides a graphical interface for exploring, querying, and managing RDF repositories. As shown in Figure 7, a total of 4494 statements have been entered by tutors. The lower section displays the action IDs, properties, and values stored as RDF triples, while the upper section shows the SPARQL query. Numerous query templates (shown on the right side of the database page) were created, and corresponding SPARQL queries were programmed to generate machine analysis results, which are displayed in the first tab (Figure 2) of the user interface.

Figure 7: Database AllegroGraph



4. Discussion

This section outlines the rationale and mechanisms behind the design of the tutoring elements, focusing on learning through tutoring preparation.

4.1 Tutoring Elements

We structured the properties of tutoring actions as follows (in alphabetical order): "action_type," "description," "difficulty," "executed_by," "follow," "guidance," "ID," "indicates," "is_correct," "learning_goal," "reaction_to," "slide," "sub_action", and "tutoring_goal" (see Figure 5). In RDF format, multiple words are connected with underscores ("_") to ensure machine recognition of these as predicate words.

Not all properties need to be applied to every tutoring action. However, essential properties such as "action_ID," "executed_by," and "action_type" are required. We incorporated pop-up prompts to ensure these properties are added when the page is refreshed. Additionally, these three values serve as action node labels on the visual map, illustrating the sequence of tutoring actions. Several key properties -- "action_type," "difficulty," "guidance," "learning_goal," and "tutoring_goal" -- merit further discussion, as detailed below.

4.2 Action Type

The "action_type" can be categorized into several types: "presenting_learning_task," "raising_question," "giving_answer," "generic_action," and "signal_message," with actions executed by either the "tutor" or the "tutee." The action description specifies the content for each task, question, answer, action, or emotional message. While large language models like

GPT have demonstrated strong capabilities in answering general questions, the ability to learn through inquiry – specifically by raising questions and solving complex problems -- is crucial for effective tutoring. Abdelghani et al. (2024) emphasize that a key strategy in inquiry-based learning is question-asking. High-quality questions involve making assumptions, predicting causes, inferring results, and tackling complex tasks.

In the case of the “giving_answer” action type, we recommend that tutors include as many answers as possible, especially incorrect ones. Although no actual tutee is involved during the preparation phase, tutors can anticipate potential responses by setting the tutee’s answers themselves. This approach contrasts with traditional lesson planning, where teachers typically prepare for only one correct answer in the slides. In this tutoring preparation, however, tutors must specify the correctness of each answer and identify potential challenges if an answer is incorrect. Additionally, tutors are required to provide feedback on incorrect answers, which involves offering corresponding guidance messages and defining the level of guidance. We suggest varying the levels of guidance for the same incorrect answer to accommodate different responses that may arise during actual tutoring sessions.

4.3 Difficulty and Guidance Level

Difficulty and guidance levels are categorized by tutors as low, medium, or high. Each task or question should specify its difficulty level, while each answer or guidance message should indicate its corresponding guidance level. Vygotsky’s (1978) concept of the “Zones of Proximal Development” (ZPD) describes the range between what students already know and what can be learned with the help of intermediaries. In this context, guidance messages serve as scaffoldings within the tutoring map, aiding in the development of the tutor’s cognitive and metacognitive skills to facilitate deep thinking and complex learning.

4.4 Learning and Tutoring Goal

The “learning_goal” is entered as free text, but it is advisable to refer to Bloom’s taxonomy of cognitive and knowledge domains (Bloom, 1956). This encompasses factual, conceptual, procedural, or metacognitive knowledge, with learning goals aimed at remembering, understanding, applying, analyzing, synthesizing, or evaluating. Research on metacognition (Rivas et al., 2022) suggests that critical thinking improves when metacognitive strategies are employed. Metacognition -- awareness of one’s thinking processes -- enhances knowledge acquisition and plays a crucial role in fostering critical thinking in higher education.

The “tutoring_goal” section is the most comprehensive in the editing help and is where tutors can derive significant benefits from their lesson planning. This section encompasses a variety of strategies, including “abstract,” “add_representation,” “challenge,” “chunk,” “contextualize,” “diagnose,” “explain,” “generalize,” “increase_difficulty,” “inform,” “model,” “motivate,” “provide_analogy,” “provide_answer,” “provide_ example,” “reduce_difficulty,” and “specify” (see Figure 8). Since these strategies may be unfamiliar to novice tutors, we provide these options for reference to assist with the metacognitive aspects of tutor reactions.

Among these tutoring goals, “abstract” and “specify” represent opposing approaches: “abstract” involves generalizing to form conclusions, while “specify” entails providing detailed examples. “Diagnose” is commonly used to identify gaps in a tutee’s knowledge, while “motivate” serves as emotional encouragement during challenging times. Strategies such as “provide_analogy,” “provide_answer,” “provide_example,” “inform,” “add_representation,” “model,” and “chunk” are effective in reducing difficulties. Additionally, there are strategies designed to increase challenges and push students’ cognitive abilities.

Figure 8: Tutoring goal

Help with editing:
tutoring_goal means: The tutor's intention for a specific action .

value	value_definition
Abstract	Explain more conceptually or abstractly.
Add_representation	Add an image or other representations for a text.
Challenge	Challenge the tutee's understanding.
Chunk	Split an action into sub-actions (chunks).
Contextualize	Provide a context for something abstract.
Diagnose	Find out what the tutee knows or what is behind a problem they face.
Explain	Explain in detail.
Generalize	Make a general statement or draw a broader conclusion.
Increase_difficulty	Increase the difficulty of a question, task, or explanation.
Inform	Inform information or knowledge.
Model	Provide a demonstration for the tutee to follow or emulate in the learning process.
Motivate	Positive stimulation and encouragement.
Provide_analogy	Provide an analogy or a metaphor.
Provide_answer	Provide an answer.
Provide_example	Provide a concrete instance.
Reduce_difficulty	Reduce the difficulty of a question, task, or explanation.
Specify	Make it more specific and explicit (inverse to Abstract).

4.5 Follow and Reaction

"Follow" and "reaction_to" are two types of relationships depicted in the tutoring map, representing sequential and responsive connections between actions. According to Brandon's Inferentialism theory in science education (Brandon, 1994; 2000), semantic expression should be regarded not merely as a transition from internal to external understanding but rather as a means to make implicit connections explicit. This perspective challenges traditional linguistic views of semantics. Similarly, Causton (2019) advocates for creating an environment where students can test new concepts, explore internal connections, evaluate how these align with their previous reasoning, and determine subsequent actions.

Inferentialism offers an innovative approach to learning design that aligns with constructivist theories and emphasizes the careful development of students' scientific understanding. This approach underscores the requirement to design learning tasks that engage students with scientific content and the semantic patterns inherent to the scientific domain. In our learning design, consequently, students engage in scientific practice by performing inferential actions on practical problems and interacting with peers within the same domain.

5. Conclusion

Our study extends upon existing research in peer tutoring by shifting the focus to the tutoring preparation stage and introducing semantic tutoring maps as a strategy to enhance learning through tutoring. This innovative approach strengthens the connection between tutoring maps and computational thinking.

We recommend two key actions for education researchers and practitioners: (a) The tutoring map, functioning as a network, can serve as a graphic organizer for lesson preparation, thereby facilitating deeper learning for student tutors. (b) Beyond merely encompassing learning content, the tutoring map integrates pedagogical knowledge, making it a powerful tool for disseminating tutoring expertise online.

Future research will focus on conducting empirical studies of peer tutoring in science contexts to evaluate the effectiveness and adaptability of this design, further advancing peer-assisted learning and collective knowledge construction.

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