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DEVELOPMENT ARTICLE

Understanding and managing the complexities in situated learning in immersive virtual environments

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Abstract

Situated learning has been widely promoted in educational practice, where students are encouraged to learn by exploring real-world problems in authentic contexts. To expand the opportunities for situated learning, immersive virtual environments have been explored by presenting problem contexts in vivid and interactive formats and enabling a variety of exploration activities. However, there are multiple challenges surrounding situated learning. The challenges can be caused by the complexities of real-world problems, the complexities in exploring real-world problems, and the complexities in reflecting on the exploration experience. This paper presents a conceptual framework outlining three types of complexities surrounding situated learning and six strategies for coping with these complexities. A case of situated learning curriculum in an immersive virtual environment is used to illustrate how the framework works in practice. By presenting a high-level and holistic picture of the challenges in situated learning along with the coping strategies, the proposed framework enriches the understanding of situated learning. It can serve as a guide for designing situated learning curricula, evaluating situated learning practices, and addressing situated learning challenges.

Keywords Situated learning · Complexity · Conceptual framework · Immersive virtual environment · Real-world problem solving · Inquiry learning

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Introduction

In view of the compelling need to deal with complex problems and novel situations in an increasingly dynamic and competitive world, learning by exploring real-world problems and real-life situations has become more important than ever. This can be referred to situated learning, i.e., learning that takes place in authentic settings, where students are encouraged to explore real-world problems bound to physical and social environments (Brown et al., 1989; Lave & Wenger, 1991). Situated learning provides plenty of opportunities for students to apply abstract knowledge and principles, develop problem-solving skills, collaborate with others, and connect learning with their lives and communities (Dawley & Dede, 2014; O'Brien & Battista, 2020). It has been widely promoted in educational practice mainly by engaging students in various problem-solving activities.

Given the constraints of classroom settings in offering situated learning, virtual and simulation environments such as virtual worlds and video games have been applied to expand the opportunities for learning in authentic settings (Chernikova et al., 2020; Dawley & Dede, 2014; Jacobson et al., 2016; Spector, 2002). These applications have shown their potential to engage and empower learners in problem-oriented, socially situated settings by presenting problem contexts in vivid and interactive formats and enabling a variety of exploration activities, such as interaction with objects, data collection and analysis, and collaborative construction of learning artifacts (Coban et al., 2022; Radianti et al., 2020; Zhou et al., 2022).

While it is commonly agreed that situated learning has great potential to promote student learning, the advantages of situated learning are not always evident (Aditomo & Klieme, 2020; Furtak et al., 2012; Gijbels et al., 2005). Whether in a physical or virtual environment, learning to solve real-world problems often involves complex processes, which may place high demands on learners' ability to solve complex problems. Educational researchers have discussed the importance of guiding or scaffolding learning in problem-solving contexts, allowing learners to accomplish complicated tasks with appropriate support (Hmelo-Silver et al., 2007; Kirschner et al., 2006; Lazonder & Harmsen, 2016; Wang et al., 2016). Empirical studies have demonstrated promising effects of scaffolding student learning in problem-solving contexts (elaborated in"Scaffolding situated learning"section). However, there is a lack of holistic understanding of the complexities surrounding situated learning and how to properly address these complexities while maintaining the open-ended nature of situated learning. Such an understanding is critical to realizing the full potential of situated learning.

This paper presents a conceptual framework that outlines the complexities in situated learning and relevant approaches to addressing these complexities. While situated learning can take place in classrooms and real-world settings, situated learning in virtual environments has been increasingly promoted in educational practice. The proposed framework aims to provide an extended understanding of situated learning and a landscape of strategies for enhancing situated learning in virtual environments.

Situated learning

Situated learning theory holds that effective education requires learning embedded in authentic contexts of practice, rather than in decontextualized and abstract forms. The theory was explicitly put forward by Lave and Wenger (1991), who argued that knowledge is co-constructed through communities of practice. Situated learning is closely related to situated cognition theory, which claims that knowing is inseparable from doing since all knowledge is situated in activities bound to physical, social, and cultural contexts (Brown et al., 1989). The two theories share a common view that situation and cognition are interdependent; cognition is a process that occurs in physical and social contexts wherein knowledge is created and applied. The two theories also align with experiential learning or learning-by-doing theories, which emphasize the creation of knowledge through the transformation of practical experience (Dewey, 1938; Kolb, 1984). These theories have been widely applied in educational practice in particular by promoting problem-centered learning and instruction (Merrill, 2002).

Situated learning has been promoted in educational practice with a focus on encouraging students to learn by exploring real-world problems in authentic contexts. It is characterized by the following key features: (a) connecting abstract knowledge with real-world problems; (b) engaging students in authentic practice in physical and virtual environments; and (c) promoting student-centered learning by enabling students to play an active role in the learning process while teachers are facilitators of student learning.

Situated learning about real-world problems

Situated learning is primarily aimed at helping students develop a meaningful understanding of complex knowledge (such as abstract concepts, scientific facts, and complicated principles), which is difficult to transmit via expository teaching methods. Moreover, it aims to help students develop problem-solving skills by working with real-world problems in authentic contexts. Students involved in situated learning are expected to engage in authentic practice mainly through two forms of tasks, inquiry-based tasks and design-based tasks (Chen et al., 2025; Thibaut et al., 2018).

In inquiry-based tasks, students are encouraged to explore real-world problems or natural phenomena by engaging in relevant activities such as making observations, posing questions, collecting and analyzing data, formulating and justifying hypotheses, forming conclusions, and communicating results (Lazonder & Harmsen, 2016). For example, in the study of Quintana et al. (2001), ninth-grade students studied environmental science by investigating air quality; they worked in pairs to set up driving questions, gather and analyze data, and build system dynamics models to explain their findings. In the study of Knezek and Christensen (2020), middle school students used energy monitoring machines to audit the consumed power of their home appliances and applied scientific knowledge and mathematical models to analyze the data to investigate climate change issues.

In design-based tasks, students are encouraged to create solutions (e.g., models, products, proposals) to address real-world problems or practical issues through an iterative process that may involve defining the problem, designing solutions to solve the problem, and testing and refining the solutions (Roehrig et al., 2021). For example, in the study of Hjorth and Wilensky (2019), students constructed cities through computer simulations, which enabled them to change the city's infrastructure and observe the emergent results of the infrastructure changes;

the task was designed to improve students' causal reasoning skills. In the study of Grizioti and Kynigos (2021), students were asked to play, modify, and co-create games that simulated real-world issues; the task was designed to help students make sense of complex real-world problems and develop systems thinking skills.

Situated learning in virtual environments

With the support of technological advances, virtual and simulation environments have been used to expand the opportunities for situated learning. They can be referred to (immersive) virtual reality, augmented reality, video games, and digital environments that offer simulations of phenomena (Coban et al., 2022; Radianti et al., 2020). Immersive virtual reality is a three-dimensional, computer-generated environment that provides a sensory illusion of being present in another environment; it allows users to experience deep immersion, presence, and interactivity through specific technology devices (Coban et al., 2022; Radianti et al., 2020). In most studies, students use their virtual avatars in virtual environments, interact with digital objects, and communicate with others; they often work in small groups to collect and analyze data, generate and test hypotheses, or construct learning artifacts.

For example, in the study by Hanna et al. (2014), secondary school students interacted with a virtual learning environment to investigate why the populations of certain species of animals on a fictitious island declined; they explored the problem by collecting relevant data about the current and past states of the island and collecting evidence from different perspectives via interacting with different virtual agents (e.g., hunter agent, climatologist agent, ecologist agent) to determine the possible causes of the increased death rates of some populations. In the study of Bressler and Bodzin (2016), eight-grade students investigated a mysterious chemical powder by using a mobile educational game designed with augmented reality; they worked in small groups to investigate the powder by conducting hands-on experiments and collecting and analyzing evidence, during which they interacted with the game to receive prompts and inserted the information about their results back to the game.

Further to immersive virtual reality, augmented reality (AR) or mixed reality has been explored to enhance interactive experience in situated learning. AR is an interactive experience that combines the real world and computer-generated three-dimensional content by adding layers of virtual objects to the real environment (Coban et al., 2022; Radianti et al., 2020). For example, Oh et al. (2018) designed a multiuser participatory simulation to support the learning of complex concepts (e.g., the refraction of light) through full-body immersion by using projection-based AR, optical see-through AR glasses, and gesture technology.

By utilizing the rich affordances and capabilities of immersive technologies and digital media, immersive virtual environments offer unique and engaging environments to support situated learning (Dawley & Dede, 2014; Radianti et al., 2020; Zhou et al., 2022). Research has shown their promising effects on improving students' engagement and intrinsic motivation as well as knowledge and skills by fostering open-ended exploration, student-centered learning, and collaboration experience (Coban et al., 2022).

Scaffolding situated learning

Situated learning has focused on engaging students in real-world problem-solving tasks to develop problem-solving skills and construct knowledge from the tasks. Solving real-world problems often involves complex processes that are difficult to predefine. This is because real-world problems are often ill-defined problems characterized by incomplete information and the lack of well-determined algorithms to solve the problem (Hmelo-Silver & Barrows, 2015; Jonassen, 1997; Kirschner et al., 2006). While students are encouraged to learn by solving real-world problems in physical or virtual environments, they face a variety of challenges that may hinder their learning process (Wang, 2024). The challenges are associated with the complexities surrounding situated learning, which involve the complex nature of real-world problems, the dynamic process of exploring real-world problems, and the difficulty of making sense of problem-solving experience for effective construction of knowledge from the practice.

As noted in relevant literature (Kirschner et al., 2006; Klahr & Nigam, 2004; Mayer, 2004), exploring complex real-world problems may impose a heavy cognitive load on learners, which is detrimental to learning; pure discovery learning with minimal guidance can be less effective than guided inquiry. This view echoes the cognitive apprenticeship model, which claims that carrying out a complex task usually involves implicit processes; it is essential to make these processes visible for novices to observe and practice with the necessary guidance (Collins et al., 1991). Findings from empirical studies have revealed the importance of guiding and scaffolding student activities in complex inquiry and problem-solving contexts (Hmelo-Silver et al., 2007; Lazonder & Harmsen, 2016).

Various methods and strategies have been employed to guide situated learning. Direct instructions provide learners with immediate guidance and the information they need to accomplish their tasks. More attention has been paid to indirect instructions, that is, making the complex aspects of learning tasks accessible to learners by guiding learning activities in productive directions. Indirect instructions are often deployed as scaffolding, which refers to a variety of instructional techniques that help learners reach higher levels of comprehension and skill acquisition that they would not be able to achieve without such assistance (Devolder et al., 2012). The approaches for scaffolding student learning about complex problems in authentic contexts have focused on revealing the complexity of learning tasks, such as structuring or decomposing a complex task into a set of activities for easy access (Quintana et al., 2004; Reiser, 2004). For example, in the project "knowledge integration environment" led by Linn et al. (2006), student exploration of the problem "How far does light go?" was guided by a set of activities: collecting evidence from scientific sources, gathering additional evidence from daily life, synthesizing the evidence into a framework, and formulating a scientific argument. In the study of Houseal et al. (2014), the teachers and scientists modeled the inquiry process to guide students throughout the scientific expedition; such guidance allowed students to see the whole picture of scientific inquiry and the professional practice. Despite these efforts to support situated learning, there is a lack of holistic understanding of the complexities surrounding situated learning and how to properly address these complexities while maintaining the open-ended nature of situated learning.

Understanding and managing the complexities in situated learning

In situated learning, students are expected to play an active role in the learning process, while teachers are facilitators of student learning. To provide effective support for guiding or scaffolding student learning without undermining the open-ended nature of situated learning, it is necessary to have a holistic understanding of the complexities surrounding situated learning and provide relevant approaches to deal with the complexities. This paper presents a conceptual framework that delineates significant complexities surrounding situated learning and relevant approaches to addressing them. The complexities are outlined from three perspectives: the complexities of real-world problems, the complexities in exploring real-world problems, and the complexities in reflecting on problem exploration experience.

Complexities of real-world problems

What are the complexities?

Situated learning focuses on the exploration of the natural world and real-world problems. As mentioned above, real-world problems are typically characterized by incomplete information and the lack of well-determined algorithms to solve the problem; they can be referred to as ill-structured problems (Jonassen, 1997). Further, real-world problems are often involved in complex systems consisting of many components interacting at multiple layers of organization and in complex causal relationships (Simon, 1962). With limited experience with real-world problems, many students or novices tend to focus on surface features and local problems rather than adopting a deep and holistic view based on nested causal relationships among multiple variables in a complex system. For instance, when reasoning about natural phenomena, students tend towards simple linear causalities, obvious or local causes, and immediate effects, thereby overlooking multiple causes (e.g., sinking or floating as a result of weight and density), non-obvious but critical causes (e.g., role of microbes in matter recycling), and indirect or distal effects such as ripple effects of an ecological disaster (Grotzer & Solis, 2015).

How to deal with the complexities?

First, it is important to expose learners to real-world problems, which are often involved in complex systems consisting of multiple interactive components. Problematizing has been recognized as an important issue for learning in authentic situations (Engle & Conant, 2002; Hiebert et al., 1996; Reiser, 2004). The core idea of problematizing is that students are encouraged to challenge, to question, and to be curious rather than simply assimilating facts, procedures and other “answers”. To do so, learners should be allowed to experience the complexities of problems by immersing them in authentic situations that consist of a number of components interacting in complex ways. Such experiences will help learners make sense of the world from a complex system perspective, as advocated in the literature on systems-thinking and complexity in education (Jacobson & Wilensky, 2006; Wilensky & Resnick, 1999). A complex system perspective is crucial to understanding and dealing with ill-defined problems in today’s increasingly dynamic and competitive world. Given the constraints of classroom settings, computer simulations and immersive technologies have been increasingly used to enable learners to access such complexities via interaction with simulated real-world problems in virtual environments. Research on situated learning in immersive virtual environments (e.g., Barab et al., 2005; Grizioti & Kynigos, 2021; Hanna et al., 2014; Hjorth & Wilensky, 2019; Kamarainen et al., 2015; Ketelhut et al., 2010) has demonstrated the potential of such approaches, which allow students to access complex ecological and epidemiological problems in richly simulated natural and urban environments that contain multiple complex interactive components, such as living organisms (e.g., different species), nonliving components (e.g., water, air, soil), external factors (e.g., weather), and human activities.

Second, learners should be provided with necessary learning resources and non-critical aspects of complex practice should be simplified. The notion of problematizing mentioned above involves productive complexity, which suggests a balance between engaging students with complex problems and preventing them from nonproductive practices that merely increase their cognitive load (Reiser, 2004). Productive complexity encourages an optimal level of complicacy instead of overwhelming complexity. In doing so, non-critical aspects of complex practice in situated learning, such as managing various data generated during the investigation, can be simplified to help learners focus on key learning objectives and reach an optimal state of concentration (Csikszentmihalyi, 1991). For example, in the studies on inquiry learning of ecosystems and natural selection (e.g., Dede et al., 2017; Reiser et al., 2001), graphs were automatically generated based on the data collected by the students, which helped students concentrate on comparative analysis of the data to test their hypotheses, minimizing the distractions caused by saving and retrieving the data.

Moreover, the information or learning resources relate to the problem domain and necessary skills or strategies for inquiry and problem-solving should be provided to learners. The exploration of real-world problems involves a range of activities such as data collection and analysis, hypothesis generation, and reasoning with data. These activities require the use of operational skills and heuristics and cognitive strategies (de Jong & van Joolingen, 1998; Kyle, 1980), which are typically tacit and contextualized, and not easily mastered by novices. In such contexts, students need instructions on how to use relevant skills and strategies to perform exploratory tasks in a given context.

Complexities in exploring real-world problems

What are the complexities?

Situated learning emphasizes learner autonomy in working with open-ended real-world problems. The exploration processes often involve iterative cycles of gathering information through observations and experiments, generating hypotheses, reasoning and explanations with data, and drawing conclusions. What might be a connected set of actions from an expert perspective might be a set of discrete, cognitively demanding steps for a novice. They tend to be distracted by less important aspects if they are not mentored during the exploration process (Quintana et al., 2004). In short, it is not easy to conceptualize the goals or determine the most relevant actions to accomplish an open-ended exploration task.

Further, it is difficult to complete the complex dynamic process of exploring real-world problems. Completing a problem-solving or inquiry task often involves a complex dynamic process rather than a fixed sequence of well-defined activities (Jonassen, 1997; Newell & Simon, 1972). For example, after collecting information about the problem, learners need to analyze the data; the analysis output may update their understanding of the problem and influence their decisions concerning subsequent actions to explore the problem (e.g., seek additional information or formulate hypothesis). In particular, the process of reasoning with data of multiple variables interacting in complex ways is complicated and has received increased attention in inquiry learning (Chinn & Malhotra, 2002).

How to deal with the complexities?

First, it is important to consolidate sets of key actions into heuristics or cognitive strategies as general methods for exploring real-world problems. Research on addressing the complexities in exploring real-world problems has focused on structuring or decomposing an open-ended, complex exploration task into a set of main actions or key questions based on heuristics or disciplinary strategies, which help learners recognize the important goals to pursue in the exploration (Reiser, 2004). For example, in the study by Sandoval (2003), students were asked to investigate why most finches on a fictitious island died, while some were able to survive during a period of drought; the exploration was guided by structuring the task into three main actions: creating research questions and sub-questions, constructing candidate explanations and associating them with research questions, and providing evidence for each assertion. To prevent such heuristics from being ritually as opposed to thoughtfully applied, it is important for students to see them being modified in certain contexts and repurposed for new contexts.

Second, the implicit aspects of the exploration process should be made visible to learners. Although heuristics and cognitive strategies can provide general methods for exploring real-world problems, students may have difficulties completing the entire process. During the task, learners need to go through a complex dynamic process instead of a fix sequence of activities involving searching for relevant information, integrating problem information with subject knowledge, engaging in reasoning about various data, and formulating and revising hypotheses. Many students have difficulties moving forward productively in the exploration process. In this context, it is important to externalize the implicit or "hidden" aspects of the exploration process to learners, for example, by providing prompts (Ge & Land, 2003) and by visualizing the task process using process maps or flowcharts (Wang et al., 2013). In the study of Wang et al. (2013), students were provided with a process map that supported their problem-solving process by visualizing the key elements of the process and showing detailed guidelines for each element in the process.

Complexities in reflecting on problem exploration experience

What are the complexities?

Achieving desirable learning outcomes from situated learning depends not only on participation in problem-solving activities but more on making meaning of the experience. The latter refers to engaging students in active reflection and communication about what they have performed and thought in problem-solving activities. In doing so, students need to coordinate their "doing" and "thinking", which echoes the synthesis of behaviorist and cognitive perspectives of learning (Greeno, 1998). The reflection or sense-making process can help students consolidate their understanding of abstract ideas, identify the gaps in their knowledge and performance, and construct new understanding from the experience. Moreover, reflection can foster knowledge transfer, which is crucial to education (Hajian, 2019; Perkins & Salomon, 1992). Problem-solving experience in virtual environments may not be directly transferable to other contexts (Dawley & Dede, 2014). Prior research has highlighted the importance of connecting problem-solving and knowledge-construction processes for effective learning and knowledge transfer in situated learning contexts (Wang et al., 2013).

However, it is not easy for students to engage in effective thinking and reflection to develop a meaningful understanding of problem exploration experience. Students may face two complexities. *First*, it is not easy to focus on the important aspects when reflecting on problem exploration experience. Meaningful understanding of the experience requires the internalization of the discourse forms of a discipline (Mercer, 2013), which is regarded as the norms of thinking used by people in a subject community to describe and communicate their mental states and mental processes such as argument and inference (Tishman & Perkins, 1997). Students who are unfamiliar with the ways and norms of thinking that are important to the discipline tend to be distracted by surface experience or desired results and unable to think in a systematic way (Krajcik et al., 1998). For example, many students tend to present data and state conclusions without explicitly building relations between the two (Germann & Aram, 1996).

Second, it is difficult to communicate complex ideas when reflecting on problem exploration experience. Meaningful thinking and reflection on the exploration experience requires the use of language or other forms of representation to articulate or communicate complex ideas. For instance, people use thinking-aloud approaches to verbalize and explain their thinking and actions when they carry out tasks (Boren & Ramey, 2000; Ericsson & Simon, 1980) or use learning journals to reflect on the learning experience (McDrury & Alterio, 2003). Larkin and Simon (1987) claimed that verbal text alone is limited in representing the understanding of complex issues, and a diagram is sometimes worth a thousand words. If used appropriately, graphic formats can reduce people's cognitive load through meaningful representation of abstract ideas and by virtue of the brain's capacity to process visual images rapidly (Scaife & Rogers, 1996).

How to deal with the complexities?

First, disciplinary norms of thinking should be made explicit to learners for effective reflection on problem exploration experience. For example, in the study by Engle and Conant (2002), 5th-grade students engaged in a field trip to investigate how endangered animals such as whales survive. During the investigation, students searched for references, conducted interviews with experts, and debated with peers. When sharing their experiences and findings, students were explicitly urged to provide relevant evidence from books, videos, discussions, and consultation emails, and use evidence-based arguments to support, challenge, or reject their claims. In another study on inquiry learning of ecosystems, students were advised to use longitudinal and cross-sectional comparisons as a disciplinary strategy to report their findings about the changes in the population data of plants and animals (Reiser et al., 2001). Such guidance can help learners reflect on and communicate their experience and regulate their problem-solving activities by following disciplinary norms of thinking or focusing on important aspects of the exploration task (Engle & Conant, 2002; Pea, 1993; Quintana et al., 2004; Tishman & Perkins, 1997) and reflecting on the gap between their performance and expert performance (Wang et al., 2018b). Furthermore, disciplinary norms of thinking can be regarded as a kind of abstraction of problem-solving methods or strategies that can foster knowledge transfer (Hajian, 2019; Perkins & Salomon, 1992). They can guide students to engage in effective reflection to capture general methods or strategies that can be reused in other contexts.

Second, visual forms can be used to communicate complex ideas about exploring real-world problems. Graphic formats and visual displays have been found to play an essential role in improving communication, understanding, and integration of complex ideas (Alexander et al., 2015; Lee & Spector, 2012; Linn et al., 2006; Woloshin et al., 2023). In particular, cognitive tools like concept maps, reasoning map, evidence map, and causal models have been used to communicate thinking and understanding in complex situations (Jonassen, 2005; Wu & Wang, 2012). For example, in the project by Toth et al. (2002), students constructed evidence maps that included data, hypotheses, and evidential relations between data and hypotheses to support their inquiry activities. Metcalf et al. (2000) developed the "Model-it" tool for students to represent and explore causal networks by specifying both qualitative and quantitative relations between variables. In the study of Wang et al. (2018a), students constructed an integrative cognitive map involving a conceptual map representing subject knowledge underlying the problem and a procedural map representing the hypothetical reasoning process when they worked with clinical diagnostic tasks in a virtual environment. Such cognitive tools are often incorporated into virtual learning environments to facilitate student thinking during the task process.

A conceptual framework

Based on the above analysis and discussion, Table 1 outlines the conceptual framework about three types of complexities surrounding situated learning and six strategies for coping with them.

Table 1 Situated learning: Complexities and coping strategies

Complexities	Coping Strategies
Complexities of real-world problems	
Real-world problems are often involved in complex systems consisting of multiple components interacting in complex ways	(1) Exposing learners to real-world problems that are often involved in complex systems consisting of multiple interactive components (2) Providing learners with necessary learning resources and simplifying non-critical aspects of complex practice
Complexities in exploring real-world problems	
It is difficult to conceptualize the goals or determine the most relevant actions to accomplish an open-ended exploration task	(3) Consolidating sets of key actions into heuristics or cognitive strategies as general methods for exploring real-world problems
It is difficult to complete the complex dynamic process of exploring real-world problems	(4) Making the implicit aspects of the exploration process visible to learners
Complexities in reflecting on problem exploration experience	
It is not easy to capture the important aspects when reflecting on problem exploration experience	(5) Making disciplinary norms of thinking explicit to learners for effective reflection on problem exploration experience
It is difficult to communicate complex ideas when reflecting on problem exploration experience	(6) Using visual forms to communicate complex ideas about exploring real-world problems

A case

How might this framework work in practice? We illustrate the proposed framework using the case of a multi-user virtual environment (MUVE)-based situated curriculum. Research on MUVE-based situated curricula for teaching and learning of biological systems in secondary science has been conducted at Harvard Graduate School of Education in the *EcoMUVE* project (https://ecolearn.gse.harvard.edu/). The *EcoMUVE* curriculum is developed based on national middle school science standards. It aims to help students understand ecosystems and complex causalities in ecosystems (Grotzer et al., 2013; Kamarainen et al., 2015). The MUVEs is a 3D virtual world that can be accessed via computers. The immersive interface allows students to explore a virtual pond and the surrounding watershed (see Fig. 1, left part). Students work individually at their computers and collaborate in teams within the virtual world and in face-face team meetings. Students create their virtual avatars, set their preferences (e.g., gender, skin color), use the avatars to communicate with team members (see Fig. 1, middle part), and interact with digital objects and no-play characters such as virtual residents (see Fig. 1, right part). To investigate why many of the fish died overnight in the pond, students observe simulated organisms over a number of virtual "days", collect relevant data, and analyz cause-and-effect relationships between variables. Below is the illustration of the complexities involved in situated learning using the *EcoMUVE* curriculum and the approaches for dealing with the complexities based on the proposed framework.

Exposing learners to real-world problems that are often involved in complex systems consisting of multiple interactive components

The pond environment in the EcoMUVE project presents an authentic ecosystem that consists of a number of both biotic (e.g., fish, algae, bacteria) and abiotic (e.g., water, air, minerals) components interacting in complex ways. The curriculum was designed based on a scenario of eutrophication, in which fertilizer runoff into the pond leads to an algae bloom. Due to algae's rapid reproduction rate and very short life cycle, dead algae accumulate in the pond and then decay very quickly. The decay process (i.e., dead algae decomposed by bacteria) uses up the dissolved oxygen in the water, making the larger fish (e.g., bluegill and largemouth bass) unable to survive. The decomposition of dead algae and dead fish adds additional minerals to the water, which leads to further algae blooms and subsequent intensive decomposition, using up the oxygen dissolved in the water and making many fish die.

Fig. 1 Screenshots of interfaces in EcoMUVE

While many students assume that there is an isolated cause (e.g., poisoning) leading the fish to die, the fish kill is a result of complex interactions among the components in the pond system. Exposing students to complex causalities in this problem context can help them develop a deep understanding of important concepts like ecological processes (including photosynthesis, respiration, and decomposition) and the roles of producers (e.g., algae), consumers (e.g., fish), and decomposers (e.g., bacteria) in ecological processes.

Providing learners with necessary learning resources and simplifying non-critical aspects of complex practice

In situated learning about real-world problems, it is important to make a balance between engaging students with complex problems and preventing them from nonproductive practices that merely increase their cognitive load. Students should be provided with necessary learning resources and facilities to promote productive complexity. In the EcoMUVE project, two online reference tools are offered to students: a *field guide* and an *atom tracker*. The *field guide* works like an encyclopedia, helping students search for and understand relevant concepts such as turbidity and food web relationships, and to obtain knowledge about specific species (e.g., bluegill) and their characteristics (where they live, what they eat, what eats them) in the pond ecosystem. The upper part of Fig. 2 shows the field guide for some species. The *atom tracker* offers students an atomic-level view of the ecological processes (such as photosynthesis, bacterial respiration) in the pond system by allowing students to track three specific simulated atoms (oxygen, carbon, and phosphorus) in the ecological process.

Fig. 2 Screenshots of learning facilities in EcoMUVE

To avoid overwhelming complexity of the problem context, non-critical aspects can be simplified. For example, in using measurement tools to collect relevant data, students only need to click on the tool and the organism or property they want to measure; the value is then displayed, automatically saved, and can be viewed in tables and graphs. As shown in the lower part of Fig. 2, the tables and graphs make it easy to display the data over time, allowing students to focus on data analysis and reasoning about the data.

Consolidating sets of key actions into heuristics or cognitive strategies as general methods for exploring real-world problems

To investigate why many of the fish died overnight in the pond, students work in teams to navigate in the virtual environment, interact with virtual residents to gather information or evidence, use measurement tools to collect data (on the water, weather, and key species), observe changes over a number of virtual "days", communicate the findings with team members, synthesize and analyze the data, formulate and refine hypotheses, and justify the conclusion. To help learners focus on the most relevant actions for the investigation, the exploration task is structured into three main actions.

Data collection via interaction with the virtual world

Given that various data are collected from different sources, the data collection activities are performed using the jigsaw pedagogy, which allows students to play different roles in the team. The water chemist uses the virtual water measurement tool to find out what is changing in the water over time. The private investigator interacts with virtual characters to learn more about the environment (e.g., a jogger mentions that the pond smelled like sewage). The microscopic specialist uses virtual microscopic tools to check the situation of invisible elements (e.g., algae and bacteria) in the pond. The naturalist looks at the different animal species and checks the population changes.

Data synthesis and analysis

Students share collected data and assemble an extensive data set within the group. The data they collect in the virtual world automatically populates a large table, from which a graph of the variables can be automatically generated. Based on the data, they identify problem-related and problem-unrelated information, integrate and distinguish between multiple sources of evidence, and negotiate the meaning within the group.

Hypothesis formulation and verification

Students work in teams to identify multiple plausible causes as hypotheses, use evidence to support or refute their tentative hypotheses via reasoning, and return to the virtual world to collect additional data when needed. They also build a concept map together to represent and negotiate their understanding of the causal relationships in the problem context to support and justify their thinking and reasoning.

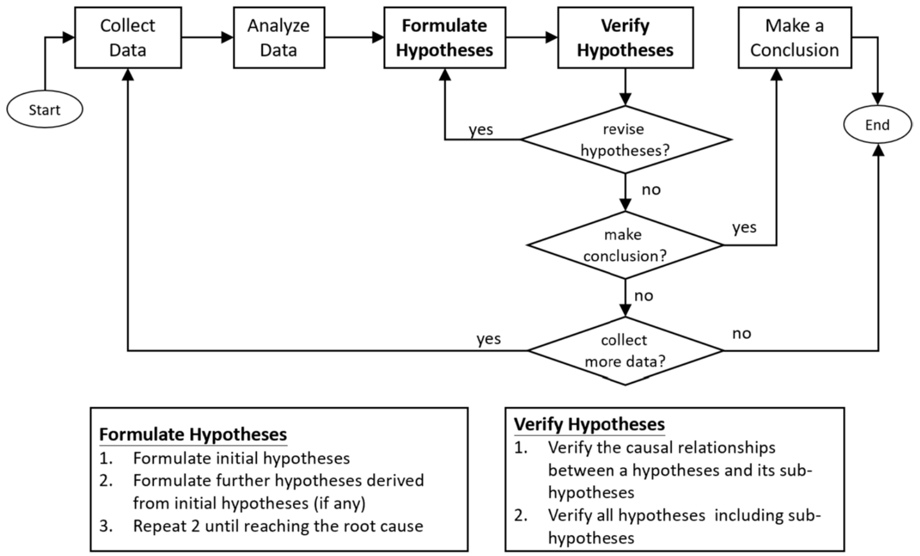

Fig. 3 Procedural guidance for accomplishing the exploration task

Making the implicit aspects of the exploration process visible to learners

Students need to go through a complex dynamic process to complete the investigation. After collecting certain information about the pond and the surrounding environment, they have to decide upon subsequent actions to move forward. Students need to synthesize the information, reason with various data, formulate and revise hypotheses, and then return to the virtual environment to collect additional data. They face the complexity of reasoning with multiple components including biotic (e.g., fish, algae, bacteria) and abiotic (e.g., water, air, minerals) components interacting in complex ways. Further, they experience the challenge of moving beyond the surface cause to uncover the root cause of the fish kill problem.

Given that students might struggle unproductively and become frustrated during the process, procedural guidance for accomplishing the exploration task can be offered to students. Figure 3 shows an example of procedural guidance, which involves a set of interactive actions including information collection, data analysis, hypothesis formulation, hypothesis verification, and drawing a conclusion. In view of the complexity in moving from the surface cause (e.g., low dissolved oxygen in water) to the root cause (e.g., algae bloom) of the fish kill problem, the steps for formulating and verifying the hypotheses at multiple levels (initial hypotheses and derived hypotheses) have been externalized in the procedural guidance.

Making disciplinary norms of thinking explicit to learners for effective reflection on problem exploration experience

Making sense of problem exploration experience is crucial to situated learning about real-world problems. To enable students to reflect on their experience in an effective manner, it is critical to make disciplinary norms of thinking explicit to them, allowing them to move from the periphery to the core of the community. In the EcoMUVE curriculum, the generic norms of developing evidence-based reasoning and specific strategies for exploring ecological problems, have been made explicit to students as follows (Grotzer & Solis, 2015; Grotzer et al., 2013).

Evidence-based reasoning

Claims or decisions are made on the basis of data and evidence collected from multiple sources. Evidence should be synthesized in a systemic way to support or refute tentative claims via reasoning.

Recognizing non-obvious causes

Essential to effective reasoning about ecological problems is the tendency to push beyond what is obvious, i.e., looking for hidden causes (e.g., role of microbes in matter recycling) that might account for outcomes even in the face of salient obvious explanations.

Observing changes over time

Reasoning for ecological problems requires attending to relevant changes over time to synthesize the evidence of ecosystems dynamics in a systemic way.

Discerning domino causality

Reasoning for ecological problems requires attending to domino causal models where effects can in turn cause other effects, making the initial root cause difficult to discern.

Using visual forms to communicate complex ideas about exploring real-world problems

External representation of complex ideas for effective thinking and reflection plays an important role in situated learning about real-world problems. To help students communicate their thinking in exploring the problem, they are asked to build a concept map in groups to represent and negotiate their understanding of complex causalities in the pond ecosystem. An example of a student-constructed concept map is presented in Fig. 4. In the concept map, students externalize complex interactions between biotic (e.g., fish, algae, bacteria) and abiotic (e.g., water, air, minerals) components in the pond system. Students utilize the concept map to reconcile the evidence from multiple sources, revise the map based on updated understanding, and formulate and justify hypotheses based on the map.

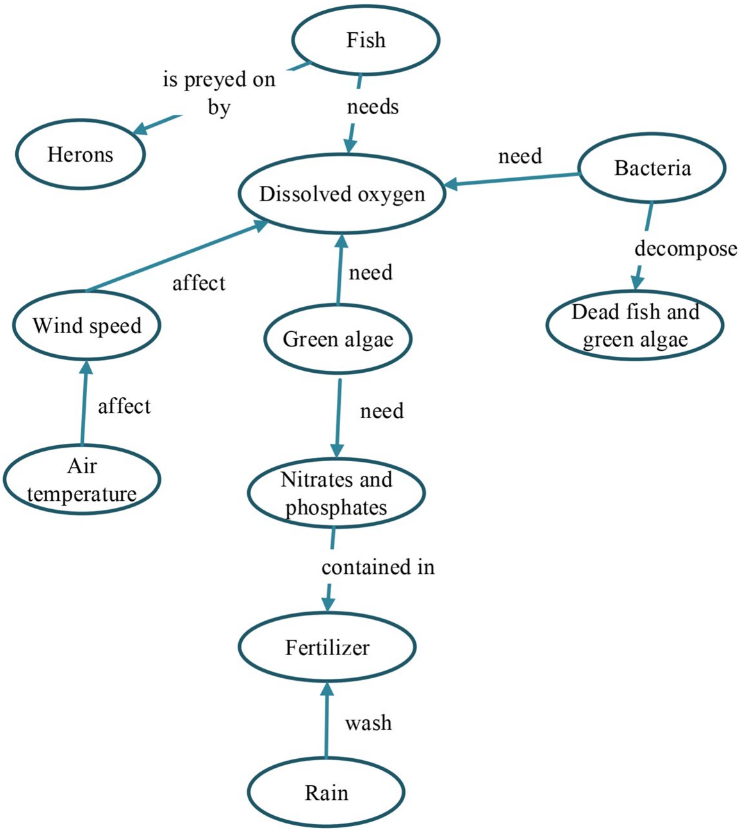

Fig. 4 An example of a student-constructed concept map

Formulating and justifying hypotheses involves a complex process of thinking and reasoning. To help students communicate and reflect on their hypothetical reasoning process, they are also asked to construct a reasoning map. Figure 5 shows an example of a student-constructed reasoning map, which represents evidential relationships between formulated hypotheses and relevant evidence from data and subject knowledge to support or reject the hypotheses. The reasoning map represents a logical series of hypotheses, including initial hypotheses and further hypotheses derived from initial hypotheses, uncovering the root cause of the problem based on the procedural guidance visualized in Fig. 5.

Findings from empirical studies

Empirical studies have been conducted using the EcoMUVE virtual environment and the proposed framework for managing complexities in situated learning. The results show that the EcoMUVE virtual environment integrated with scaffolding tools is effective in fostering deeper learning and developing transferable knowledge and skills (Dede et al., 2017). The integration of concept maps and reasoning maps can enable students to communicate complex ideas in problem-solving process, thereby improving their task performance and

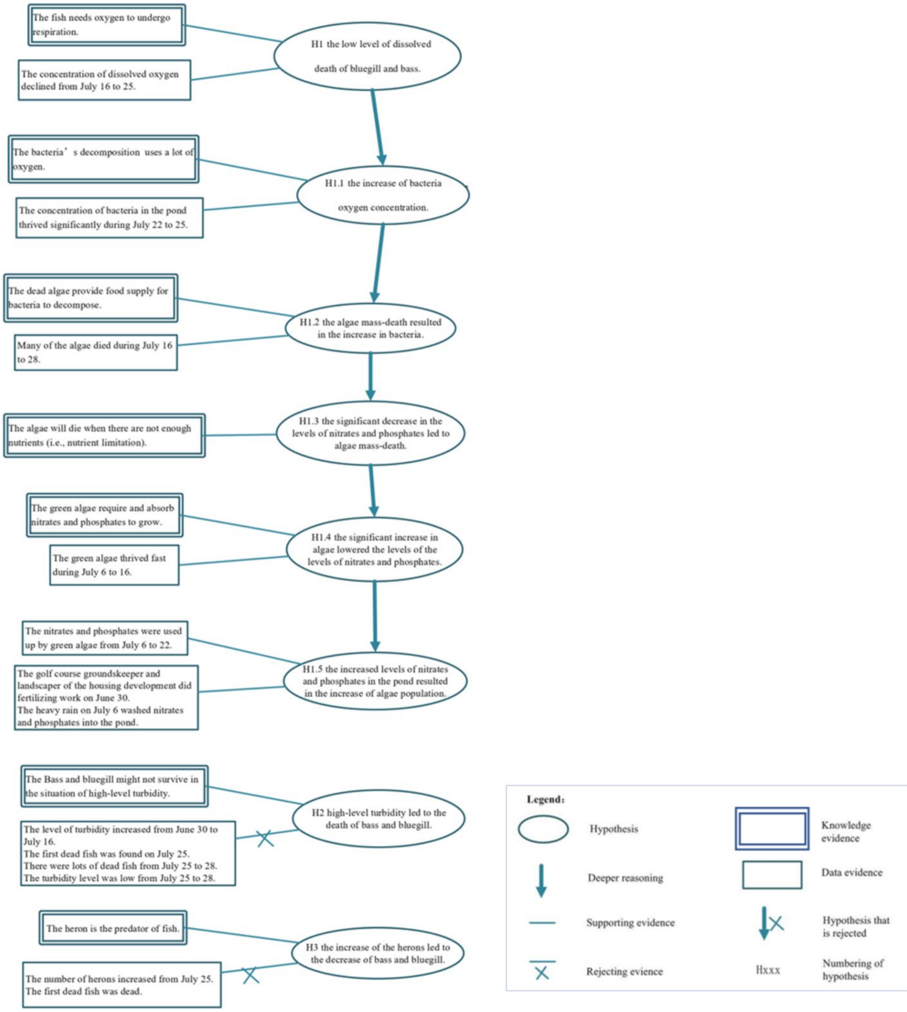

Fig. 5 An example of a student-constructed reasoning map

subject knowledge (Chen et al., 2018) and narrow the academic gap between high- and low- achieving students (Chen et al., 2017). Moreover, students' problem-solving performance can be predicted by the quality of the reasoning maps constructed by them; the latter can be further predicted by the quality of student-constructed concept maps (Chen et al., 2021). Further analysis of student performance reveals that students who presented problem situations in their concept maps achieved better performance in concept mapping and problem solving compared to other students who only presented conceptual issue in their concept maps (Chen et al., 2024).

These findings suggest that effective learning about real-world problem-solving in virtual environments requires more than immersing students in the virtual world with necessary facilities. It is important to provide students with necessary support or scaffolding for them to move forward productively in the exploration process. Furthermore, students should be guided to coordinate their "doing" and "thinking" during the exploration process. In doing so, making disciplinary norms of thinking explicit to learners and using visual forms to convey complex ideas have shown promising effects on improving student learning outcomes.

Closing thoughts

Situating learning has been widely expanded to immersive virtual environments and shown its significant impact on education. Learning in problem-oriented and socially situated settings has become particularly important in today's dynamic and competitive world given the compelling need for people to cope with novel situations and ill-defined real-world problems. In view of a variety of complexities and challenges surrounding situated learning, it is vital that researchers develop a thorough and systematic understanding of these complexities and determine how the potential of situated learning can be fully realized by addressing the complexities.

This paper presents a conceptual framework that outlines multiple complexities in situated learning together with relevant approaches to addressing them. In this framework, the complexities are delineated in three aspects: the complexities of real-world problems, the complexities in exploring real-world problems, and complexities in reflecting on problem exploration experience. A set of strategies are proposed to address the complexities.

(1) Exposing learners to real-world problems that are often involved in complex systems consisting of multiple interactive components.
(2) Providing learners with necessary learning resources and simplifying non-critical aspects of complex practice.
(3) Consolidating sets of key actions into heuristics or cognitive strategies as general methods for exploring real-world problems
(4) Making the implicit aspects of the exploration process visible to learners
(5) Making disciplinary norms of thinking explicit to learners for effective reflection on problem exploration experience
(6) Using visual forms to communicate complex ideas about exploring real-world problems.

The proposed framework offers a high-level view of the complexities in situated learning in virtual environments and the coping strategies. It is in line with the key features of situated learning in authentic problem-solving contexts. Moreover, the framework echoes the following principles for effective learning in such contexts. *First*, while it is important to provide students with necessary support to solve complex real-world problems, the guidance or scaffolding offered to students should not undermine the open-ended nature of real-world problem-solving (Dede et al., 2017). *Second*, a balance needs to be struck between engaging students in authentic practices and preventing them from nonproductive practices that merely increase their cognitive load (Reiser, 2004). *Third,* while situated learning emphasizes learning-by-doing, it is important to help learners coordinate their "doing" and "thinking" to achieve desirable learning outcomes. Effective situated learning depends not only on "doing" or active participation in authentic practice, but more on deeper thinking and reflection on the experience (Greeno, 1998). *Fourth*, considering that students are encouraged to play an active role in situated learning, it is important to foster their autonomy and independence by helping them develop meta-cognitive knowledge and skills (e.g., general heuristics for inquiry). Such kind of knowledge and skills can be referred to learning how to learn, which are often missing in most school curricula (White & Frederiksen, 1998).

Hopefully, this framework can enrich the understanding of situated learning by presenting a holistic picture of the challenges in situated learning along with the coping strategies. The proposed framework can serve as a guide for designing situated learning curricula, evaluating situated learning practices, and addressing situated learning challenges. A limitation of this paper is a lack of a systematic review of relevant studies before proposing the framework. Future research may consider conducting a systematic review of empirical studies on situated learning about real-world problems in virtual environments to synthesize the findings on the effects of relevant approaches that address the complexities in situated learning.

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