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Guided Epistemic Expansion in a Science Classroom

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Abstract: In this paper, we study students' epistemic engagement in a learning environment that uses Emergent Systems Microworlds (ESMs). ESMs are agent-based computational models that are designed as constructionist microworlds. We use Engeström's theory of expansive learning for analyzing how agent-based restructurations and constructionist design features of a learning environment facilitate the epistemic expansion of an activity system in a science classroom. We analyze three design features of an ESM-based learning environment that created generative contradictions, which allowed students to devise epistemically expansive ways using the same features to address those contradictions. We discuss how these features facilitated student learning as the students used the ESM as a computational experimental system to test and establish evidence-based claims and collectively shape epistemic practices. This work provides an approach for designing learning environments that foreground students' epistemic engagement in shaping science practices to learn about disciplinary ideas.

Introduction

In his 1991 paper, Engeström discussed approaches to overcome the encapsulation of schooling, which he defined as the artificial separation of school learning from experience, cognition, practices, and values from outside the school (Engeström, 1991). Engeström's framing of this issue goes beyond the concerns regarding designing for out-of-school learning experiences. He draws attention to the lack of direct connections between ideas that one learns in school and their relevance to everyday learning and lived experiences out of school including potential disciplinary practices. From the communities of practice (CoP) standpoint (Lave & Wenger, 1991), which Engeström discusses as one of the approaches to overcome this separation, learning is defined as the legitimate peripheral participation in a community of practice. So, what would such legitimate peripheral participation be for science students in a school?

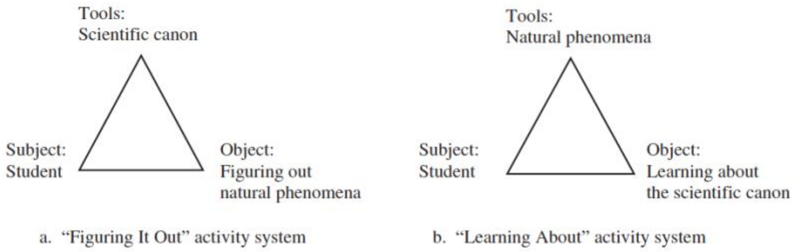
Science educators and researchers have advocated for decades that science learning should involve meaningful participation in scientific inquiry or sense-making practices to learn about disciplinary ideas (Abd-El-Khalick et al., 2004; Duschl, 2008; Schwarz et al., 2017). Such participation in science practices is intended to serve two purposes – (1) when students construct knowledge by experiencing and investigating natural phenomena in the world, they learn deeply about the science content, and (2) the engagement in the practices of scientific knowledge construction also allows students to learn about the practices themselves. Such meaningful participation in science practices requires reimagining the roles of students and teachers in the science classroom such that students become *doers of science* and not *receivers of facts* (Miller et al., 2018; Schwartz et al., 2004). For example, biology students can participate in the same practices as professional biologists, such as using agent-based computational models to investigate a biological phenomenon such as prey-predation population fluctuations or synchronization of flashing of fireflies (e.g., Wilensky & Reisman, 2006).

Having agency in shaping the community's shared knowledge construction work is an important aspect of science researcher practice (Latour, 1987). Engaging students in similar ways in knowledge construction processes requires designing learning environments that support students' epistemic agency. The term epistemic agency was introduced into education literature in relation to the research on knowledge-building communities conducted by Scardamalia and Bereiter (1991). Epistemic agency refers to students' ability to shape and evaluate knowledge and knowledge-building practices in the classroom (Scardamalia & Bereiter, 1991; Stroupe, 2014). The Next Generation Science Standards (NGSS) has recommended a set of science practices that are epistemically equivalent to those practices of scientists (NGSS Lead States, 2013). However, this framing of epistemic equivalence creates a contradiction for *doing science* using the NGSS framework (Miller et al., 2018) because encouraging students to appropriate a set of practices chosen by others does not position students with epistemic agency: the power to shape the knowledge production and practices of a community. In a classroom setting there is often a tension between teaching established disciplinary ideas and authentically participating in practices to construct knowledge (Russ & Berland, 2019; Schwarz et al., 2017). What Russ & Beland (2019) refer to as a problem of practice arises because of this tension between learning established ideas and constructing one's own ideas. The authors highlight a dichotomy between two intended objects or goals of students' activity in a science classroom using the activity theory framework (See Figure 1). This dichotomy is between "Figuring it out" vs

"Learning about" activity systems, where the former is focused on using the scientific canon to figure out a natural phenomenon and the latter is focused on using a natural phenomenon as a tool to learn about the scientific cannon.

Figure 1

Mediational activity triangles in a science classroom (From: Russ & Berland, 2019, p. 286)



In this paper, we propose a different way, an epistemically expansive way, to frame students' classroom participation based on Engeström's framework of expansive learning (Engeström, 1991, 2001) to address the problem of practice. We use expansive learning framework because it is intended to promote and capture participation in constructing a new activity system, which is what students do when they, like scientists, identify the questions that will guide their work, and the methods that will help them answer those questions most efficaciously. Using this framework, we analyze student learning in a classroom learning environment which was designed to support students' agentic participation by providing them with tools to engage in epistemic practices. We refer to this learning environment as Emergent Systems Microworld (ESM)-based learning environment. An ESM is a computational microworld designed using constructionist and agent-based modeling principles (Dabholkar et al., 2018; Dabholkar & Wilensky, 2019). Our goal in developing this curriculum was to not simply have students use the model, but to have them refine their own practice so that the kinds of agent-based computational models we provided would have value in helping them pursue their own epistemic goals. Thus, we wanted to support and guide them in engaging in epistemically expansive learning. We used the term guided because in contrast with traditional approaches to expansive learning where participants solely identify their need for and direction of change, our goal was to help encourage a specific new direction of socially constructing knowledge using scientific inquiry practices. We investigate the following research questions in this paper:

What design features of an ESM supported a guided epistemic expansion? How did these features mediate students' epistemically expansive learning?

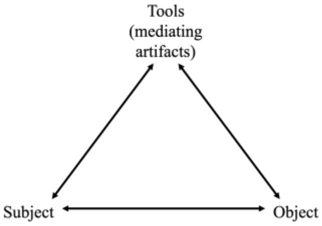
Theoretical Framework

Activity theory and expansive learning

In this paper, we analyze how an ESM-based curriculum supports the transformation of a classroom activity such that students take more agentic roles as they construct and evaluate knowledge using Cultural Historical Activity Theory (CHAT) and its extension, the theory of expansive learning by Engeström (2001). Activity theory provides a lens to design and investigate learning environments that support student engagement in social knowledge-building activities in specific domain areas such as complex systems (e.g., Danish, 2013, 2014; DeLiema, Enyedy, & Danish, 2019). The focus of such analysis is to investigate how different *tools* in a learning environment mediate individual and social transformation (Engeström, 1999).

Figure 2

Vygotsky's mediational triangle (from (Cole, 1998), p. 119)



The original activity triangle or mediational triangle, proposed by Vygotsky, explains the relationships between subject, object, and a mediating tool (Vygotsky, 1978) (Figure 2). The mediational triangle helps in understanding the object-directed nature of human action. While Engeström has since expanded the triangle to include the community, rules, and division of labor (Engeström, 2001), we find that focusing primarily on the designed mediational tools can provide clarity in our design efforts and avoid some of the challenges that arise from attempting to categorize all of the mediators in play (Witte, 2005). In a classroom setting, an object for a student is not necessarily the same as the object that is intended by a teacher for the student. The intended object is the purpose for which the activity is designed, and the enacted object is the object that a subject (student) uses a tool to achieve. This distinction becomes even more crucial when one intends to use activity theory to design and analyze a learning environment. For example, when an ESM-based learning environment is designed for students to socially construct knowledge, the object 'to socially construct knowledge' is an intended object for the students by the designer of the ESM-based curriculum. So, how can designers' intended object for students become the enacted object in a classroom activity system?

In the theory of expansive learning, Engeström (2001) discusses the possibility of expansive transformation of an activity system, in which the Object (goal/purpose) of Activity gets reimagined as subjects engage with a mediational tool. In the context of science education, such expansive transformations mean a shift in the role of students in a science class from listening and understanding to actively engaging in knowledge-building practices. In this paper, we analyze how design features of a learning environment guide such epistemic expansion such that designers' intended object becomes the enacted object.

Design Framework

ESMs and ESM-based curricula

Over the years, scientific communities across the globe have developed experimental model systems that have affordances to investigate specific aspects of natural phenomena. For example, fruitflies' (*Drosophila*) chromosomal organization and their short life span have made them a model system to study genetics. We argue that using principles of Learning Sciences computational models can be designed to be pedagogically effective model systems that support students' self-driven investigations and therefore their epistemically agentic learning within the constraints of a classroom. In this work, we designed Emergent Systems Microworlds (ESMs) as computational model systems embedded in ESM-based curricula for students to investigate a modeled emergent phenomenon in agentic ways.

ESM design combines two design approaches in Learning Sciences, namely agent-based modeling of emergent systems and constructionism (Papert, 1980; Wilensky, 2001). Agent-based representations in ESMs create affordances for learners to engage deeply with a complex emergent phenomenon (Goldstone & Wilensky, 2008; Wilensky & Reisman, 2006). An ESM is designed as a microworld using constructionist design principles to mediate students' self-driven explorations to investigate various aspects of the represented disciplinary ideas (Edwards, 1995; Papert, 1980). An ESM-based curriculum and accompanying pedagogical practices are intended facilitate such student engagement in self-directed, interest-driven explorations and investigations using an ESM. Students are encouraged to share their findings and participate in teacher-guided reflections to collaboratively construct knowledge about the modeled complex phenomenon in an ESM. Our design goal for the ESM-based learning environment was to support students in seeing their participation in epistemically agentic ways – as producers, consumers and evaluators of knowledge.

ESM-mediated Guided Epistemic Expansion

As we discussed before in a learning environment designed for epistemically expansive learning, the intended object 'social construction of disciplinary knowledge' must become the enacted object of classroom activity. Though this framing is inspired by Engeström's theory of expansive learning, there is an important distinction in our framing and Engeström's. Engeström focuses on inherent contradictions creating a driving force for change such that new cultural patterns are produced in the activity system, which are often previously unimagined (Engeström, 1991, 1999); whereas an ESM-based curriculum is designed to *guide* a transformation of an activity system to make its enacted object to be 'social construction of disciplinary knowledge'. To underscore this distinction, we use the term *guided epistemic expansion* to refer to the ESM-mediated transformation of a classroom activity system.

Cole (1998) expanded the concept of mediational tools to include representations that communicate the community's norms, beliefs, and understandings, as well as cognitive structures that guide action and thought (Cole, 1998). This extended concept of mediational tools becomes important in the context of designing a learning environment. Different features of a learning environment can be considered as tools to analyze how they support different intermediate activities that build towards change in an activity system. These features can act as tools to mediate student activity by supporting or constraining an action. Analysis of these features as mediational tools allows deeper insights into learning activities in an environment designed to support certain forms of learning. The mediational tools in our work are the design features of an ESM, which is a constructionist agent-based computational model. The theory of constructionism has always foregrounded such students' epistemically meaningful participation in constructing knowledge (Papert, 1980; Turkle & Papert, 1992; Wilensky, 2003; Wagh et al., 2017).

This kind of intended epistemic expansive learning in a science classroom addresses the *problem of practice* (Russ & Berland, 2019) by building on the idea of Invented Science. The authors argue that children invent 'science' to satisfy their curiosity about why and how a phenomenon occurs. However, to achieve the object of satisfying curiosity, children need to have the appropriate cognitive resources to act as mediational tools (Elby & Hammer, 2010; Piaget, 1970; Smith III et al., 1994). In a classroom setting where teachers try to balance their time between "Figuring it out" vs "Learning about" activity systems, external tools that would provide students objects-to-think-with can serve to engage in epistemic pursuits to 'invent science' (Papert, 1980; Turkle & Papert, 1992). Analysis of such mediational tools in a learning environment using activity theory can provide insights into how students socially construct knowledge of a complex phenomenon (Danish, 2013, 2014). In this paper, we discuss how a computational model system in the form of an ESM provides students with such tools to collectively support the social construction of knowledge of the modeled phenomenon.

Methods

Participants and Setting

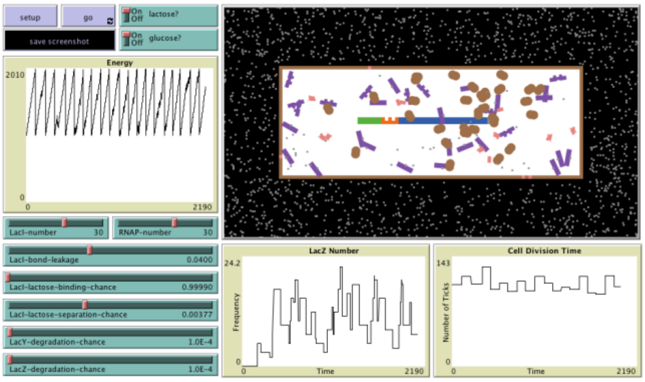
The first author was the lead designer and the lead teacher of the ESM, and the ESM-based curriculum discussed in this paper. From the methodological perspective, this made him an "unusually observant participant" and a designer (Erickson, 2006). The first author conducted these courses in two locations: twice during a weekend extra-school program for middle school students conducted by a talent-development center in a midwestern university in the United States, and twice in residential summer camps in a western city in India. The data presented in this paper is from the fourth iteration in India in which 12 students participated, of which 5 were female and 7 were male. All the students were of Asian Indian origin. We collected data in various forms, namely videos of student discussions (around 150 hours), fieldnotes, workbooks in which students wrote their observations and explanations, the computational artifacts (models, screenshots, and presentations) that students created, pre- and post-tests, and pre- and post-interviews.

GenEvo an ESM based curriculum

To engage students in constructing knowledge of disciplinary ideas regarding gene-regulatory mechanisms and evolution, we created an ESM-based curriculum, GenEvo (Dabholkar et al., 2018; Dabholkar & Wilensky, 2016). In this paper, we study students' epistemically expansive learning with the GenEvo curriculum (Dabholkar & Wilensky, 2016). This curriculum incorporates a series of four interconnected computational models designed using Wilensky's agent-based programmable modeling environment NetLogo (Wilensky, 1999). NetLogo was designed for both constructionist learning experiences and for use in scientific research. Since these four NetLogo models are strongly interconnected, they form an ESM because the underlying rules for agent behavior are consistent across the models. Using this curriculum, students can investigate the emergent properties of biological systems, including gene regulation, carrying capacity, genetic drift, and natural selection.

Figure 3

A screenshot of the first model (Genetic Switch) of the GenEvo ESM which allows students to manipulate and observe molecular interactions inside a bacterial cell



LacI-number 30

RNAP-number 30

LacI-bond-leakage 0.0400

LacI-lactose-binding-chance 0.99990

LacI-lactose-separation-chance 0.00377

LacY-degradation-chance 1.0E-4

LacZ-degradation-chance 1.0E-4

The curricular activities were designed to guide student investigations and engage students in discussing and evolving epistemic practices to establish and evaluate knowledge claims. These discussions included topics such as - *What counts evidence for a particular claim*? *What are various ways to collect, analyze and present* *evidence*? *How does one establish a claim using evidence*? Since students were using an ESM to investigate specific aspects of a phenomenon, these discussions were strongly grounded in concrete aspects regarding the biological system under investigation. Throughout the curriculum, students iteratively explored specific aspects of the phenomenon, investigated specific questions, collected evidence, and presented how their evidence supported their claims regarding the research questions.

Microethnographic analysis

To investigate students learning using the ESM-based curriculum, we conducted microethnographic analysis (Erickson, 1986, 2006) of classroom videos, specifically focusing on the dynamics of students' shifting participation in the activity and their shaping of the sociocultural practices of knowledge construction and evaluation in the classroom. Using a top-down approach, we identified instances in the field notes that indicated student engagement in knowledge construction. We performed a micro-ethnographic analysis of videos of these instances to investigate how restructuration properties of the ESM instantiated through ESM design features (mediators) and how complementing pedagogical moves by the teacher (mediation) supported student engagement in knowledge construction.

All episodes related to knowledge construction and evaluation (n = 92) were further coded using a bottom-up approach to identify the objects (the intended goals of the activity), the design features as mediating tools (mediators), and accompanying pedagogical moves (mediation). Even though the ESM is a primary mediating tool for all the activities, we coded for specific design features of the ESM to further investigate how those design features mediated different aspects of knowledge construction. We identified how these design features mediated specific intermediate objects as the activity system underwent transformation.

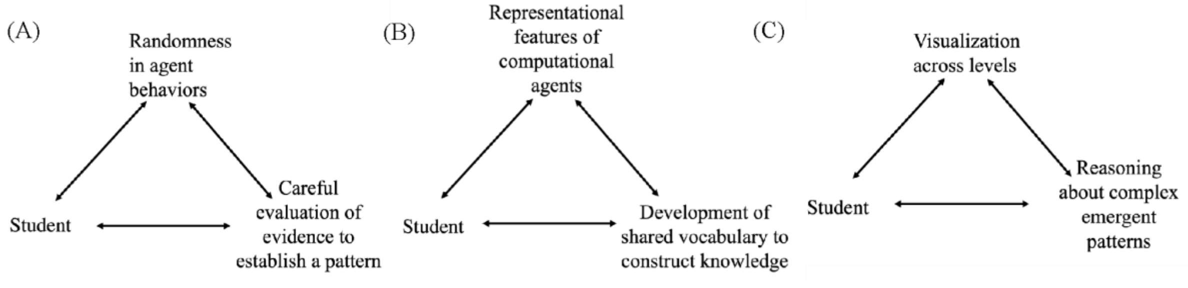
Findings

In the previous work, we have demonstrated students' learning gains regarding disciplinary ideas and shifts in their perceptions regarding their roles in a science classroom from the perspective of epistemic agency (Dabholkar et al., 2018; Dabholkar & Wilensky, 2019). In this paper, we focus on identifying and analyzing design features that mediated students' epistemically learning expansive learning. In the GenEvo ESM-based learning environment, students constructed their shared knowledge about how genetic regulation takes place in a bacterial cell as an emergent phenomenon by conducting experiments with the ESM, developing, and evaluating evidence-based claims and establishing practices to evaluate the claims.

Internal contradictions in an activity system act as a driving force for change as it undergoes expansive transformation (Engeström, 2001). We microethnographically analyzed three design features focusing on how contradictions arose because of those design features of the ESM and how the same features allowed students to find ways to address those contradictions. Our analysis helps in understanding how these internal contradictions acted as a driving force for epistemic expansion in the classroom. These design features mediated students' engagement in intermediate objects in the activity systems as they progressed with constructing knowledge of disciplinary ideas and evolving scientific practices (see Figure 3). The three objects of intermediate activity systems were (1) careful evaluation of evidence to establish a pattern, (2) development of shared vocabulary to construct knowledge, and (3) reasoning about complex emergent patterns. These objects are intermediate steps that are essential to construct knowledge about the complex phenomenon modeled in the ESM. Student enactment towards achieving these objects, in turn, mediated the transformation of the classroom activity system. The object of the classroom activity system became the social construction of knowledge about complex disciplinary ideas.

Figure 4

Intermediate activity systems in an ESM-based learning environment as the activity system underwent epistemic expansion



Randomness in encoded agent behaviors in the ESM caused slight differences in experimental outcomes, even when an experiment was repeated with identical conditions (Figure 4A). This design feature of the ESM makes the behavior of the ESM as a system close to the behavior of the real-world system (a bacterial cell, in this case) it models. Despite such stochasticity in agent behaviors, those behaviors produce consistent emergent patterns at the system level. This feature created contradictions when students tried to evaluate each other's claims. When asked for their conclusions after a curricular activity, a student, Shaurin said, "*Even with the same parameters, you won't get the same results every single time…But there is some pattern*". This was after students had investigated the effects of sugar availability in the environment on the energy of a bacterial cell. When asked further about the pattern, Shaurin and other students shared their observations and concluded that cell division time was shorter when glucose is present than other conditions, even though the observed cell division times were slightly different for all the students. In this exercise, students collectively developed an important insight regarding a practice of science, which is that there can be variability in observed data within the same experimental conditions and multiple trials need to be conducted to verify the validity of observed patterns. This led to the classroom community evolving two practices for carefully evaluating evidence: conducting multiple trials and carefully observing the mechanistic details by slowing down a model. More rigorous forms of these practices are prevalent in modern biological research: statistical analysis and time-lapse microscopy.

Another set of contradicting observations arose when students attempted to establish claims regarding the properties of specific agents and their interactions with each other because of the lack of established identities for computational agents (proteins and parts of DNA) in the microworld. These contradictions required students to develop shared vocabulary to construct knowledge (Figure 4B). While in a traditional model, a teacher might give a key or legend for the biological names of proteins and parts of DNA, in this classroom the teacher encouraged students to develop and use their naming conventions for identifying agents in the model. Students used representational features (shapes and colors) to develop a shared vocabulary for creating naming conventions for computational agents. This vocabulary evolved from "pink and purple stuff" to "pink triangles, pink rectangles, purple keys, and potato-shaped things". This incidental design feature served to engage students in an important scientific practice. Since students were investigating how molecular interactions resulted in genetic regulation at the cellular level, establishing the clarity about the identities of computational agents, their properties, and their interactions with each other was crucial. Such development of shared vocabulary is an important aspect of science practice. For example, naming conventions of organisms such as SARS-CoV-2, allows scientists across the world to easily share their findings. Representational features of computational agents in the ESM, though initially created contractions, also allowed students to devise ways to address those contradictions.

The GenEvo ESM was designed for students to visualize agent behaviors at the level of biomolecules and reason about how genetic regulation takes place at the cellular level. Students could visualize properties and interactions between biomolecules and system-level parameters such as the energy of the cell and cell division time. Discussions based on these visualizations created contradictions regarding a fundamental aspect of emergent systems: who is controlling all this – the cell, specific control molecules in the cell, or the genetic control is an emergent property of a cell. These contradictions served as a driving force for students to reason about how behaviors and interactions at micro-level result into emergent patterns at the system level (Figure 4C). Since students had designed and conducted various experiments to investigate agent-level properties, and interactions of biomolecules in different environmental conditions (presence or absence of specific sugars, glucose, and lactose) and system-level outcomes, they argued using the mechanistic details of molecular interactions to address the contradiction by reasoning how this emergent behavior at the cellular level can be manifested through interactions of biomolecules.

Discussion

In this paper, we developed a theoretical construct, *guided epistemic expansion* to name a design outcome that is intended to address the problem of practice. Our analysis of an ESM-based learning environment demonstrates how design features of an ESM mediated the *guided epistemic expansion* in the GenEvo learning environment. The findings show that three design features supported shifts towards student engagement in the social construction of knowledge about a complex phenomenon. The learning outcomes for the students were three-fold, (a) they developed knowledge about disciplinary ideas about genetics and evolution, (b) they developed knowledge about *doing science* by evolving practices to investigate a phenomenon, (c) they shifted their perceptions about their agency in the process of knowledge construction. The third learning outcome is about their *epistemic consciousness*, the realization that they can participate in constructing knowledge and devising ways to construct knowledge. One student reflected on her learning in post-interview, "*We sort of learned like how scientists would learn about the world. We do not have as much knowledge as scientists do. We formed groups, we shared ideas, we got ideas, we combined them*."

The three analyzed design features - (1) randomness in agent behaviors, (2) representational features of computational agents, and (3) visualization across levels of the ESM mediated students' engagement in specific intermediate learning goals (objects of the activity system) as they progressed with constructing knowledge of disciplinary ideas and evolving scientific practices. These three design features created contradictions as students tried to make sense of the modeled phenomenon in the ESM. These contradictions served as a driving force for the classroom community, guided by the teacher, to use the same features for addressing those contradictions. Students' enactment towards achieving these objects, in turn, mediated the transformation of the classroom activity system through epistemic expansion. The object of the classroom activity system became the social construction of knowledge about complex disciplinary ideas, which resulted in the outcome of students' expanded ideas about their participation in learning science in the classroom in epistemically agentic ways.

This work demonstrates how the design of learning environments and allied pedagogical practices to support students' epistemic agency in a science classroom can result in epistemically expansive learning. Through this work, we provide a way to address the problem of practice by providing students a computational experimental system or a playground to test and establish evidence-based claims and collectively shape practices for doing so. As students use such computational microworlds to make sense of a modeled phenomenon, contradictions created by certain design features of the ESM-based learning environment led to guided epistemic expansive learning. In the future, we would like to investigate how students make sense of their learning trajectories in such learning environments and whether they see shifts in their epistemic agency as the classroom activity systems undergo epistemic expansion.

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