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DESIGNING COMPUTATIONAL MODELS AS EMERGENT SYSTEMS MICROWORLDS TO SUPPORT LEARNING OF SCIENTIFIC INQUIRY

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Emergent Systems Microworlds (ESMs) are a special kind of computational models. Design of ESMs involves a combination of two approaches in Learning Sciences, namely agent-based modelling of complex systems and constructionism. ESMs and ESM-based curricula are frameworks for designing learning environments to foster the learning of complex scientific phenomena by engaging students in authentic scientific inquiry practices. In this paper, we discuss our approach in the context of an ESM called GenEvo that we designed for the learning of molecular genetics and evolution. We further discuss how agent-based representations and constructionist design principles mediated students' expansive learning, as students collaboratively constructed knowledge by engaging in authentic scientific inquiry practices.

INTRODUCTION

The goal of science education should not be limited to 'knowing about science', rather it should include 'learning to use science practices and tools to make sense of the world' (Duschl, 2008; Schwarz, Passmore & Reiser, 2017). Such learning would entail epistemologically meaningful engagement in science practices for sense-making, rather than merely knowing about scientific inquiry (Lehrer & Schauble, 2006; Berland et al., 2015). In other words, students should learn to construct knowledge about the world, just like scientists do. In order to support such learning in classrooms, researchers and educators are increasingly designing newer technology-enhanced collaborative learning environments and curricula that are authentic to contemporary scientific inquiry practices and provide epistemic and conceptual scaffolds for learning those practices (Chinn & Malhotra, 2002; Quintana et al., 2004). We contribute to this work of designing for computer-based collaborative science learning by combining two powerful design approaches in learning sciences: agent-based modelling of complex systems and constructionism (Wilensky & Resnick, 1999; Jacobson & Wilensky, 2006; Blikstein & Wilensky, 2010; Wagh, Cook Whitt & Wilensky, 2017). We call this design approach Emergent Systems Microworlds (ESM) (Dabholkar, Anton & Wilensky, 2018).

In this paper, we discuss an ESM about genetics and evolution, and an ESM-based curriculum that has been specifically designed to foster students' learning of scientific inquiry practices. We use Cultural Historical Activity Theory (CHAT) to analyse ESM-mediated expansive learning of science (Engeström, 2001). This is a design-based implementation research paper, in which we discuss design features of ESMs and an ESM-based curriculum, and present empirical support for the claims regarding how these features foster learning of disciplinary ideas and scientific inquiry practices.

THEORETICAL FRAMEWORK

Emergent systems microworlds

ESMs are agent-based models of emergent systems that are designed as microworlds to support students' learning through explorations and investigations of those models.

Emergent complex systems perspective involves understanding how simple interactions between autonomous elements can result in complex emergent patterns at the system level (Jacobson & Wilensky, 2006). This perspective has become a focus of real-world scientific investigations as well as recent science education reforms (Yoon, Goh & Park, 2018). Researchers of science education have argued for and demonstrated the effectiveness of emergent systems perspective for understanding natural phenomena (Wilensky & Jacobson, 2015; Wilensky & Reisman, 2006; Hmelo-Silver & Azevedo, 2006). Next Generation Science Standards in the United States has incorporated 'systems and systems models' as one of the seven key crosscutting concepts (NGSS Lead States, 2013).

Agent-based modelling of emergent systems is one of the central design features of an ESM. Such dynamic computational agent-based representations are restructurations of emergent phenomena which are typically taught with differential equations or static models (Wilensky & Papert, 2010). The agent-based restructurations have been demonstrated to be pedagogically effective to support learning of several complex natural phenomena in science education (e.g. electric current, resistance, temperature, pressure, evolution) (Sengupta & Wilensky, 2011; Levy & Wilensky, 2009; Wagh et al, 2017). The agent-based modelling approach allows students to observe behaviours of agents, and reason about emergent patterns by reducing cognitive and perceptual limitations (Goldstone & Wilensky, 2008).

The Microworlds part of an ESM is inspired by constructionist design principles (Papert, 1980). We use the 'functional' definition of microworlds as being encapsulated open-ended computational exploratory environments in which a set of concepts can be explored, through interactions that lead to knowledge construction (Edwards, 1995). A learner is expected to manipulate objects and execute specific operations instantiated in a microworld. Such manipulations would result in observable changes in the microworld. As learners observe those changes, they receive feedback through representations linked with the objects about their behaviours and changes in the system. Learners use this feedback to induce or discover the properties and functioning of the system as a whole. Through this process, they learn by self-correcting or 'debugging' their understanding of the domain to develop new powerful ideas (Papert, 1980). Constructionist learning environments in the form of microworlds have been demonstrated to be effective for learning in several contexts (Kafai & Resnick, 2012; Noss & Hoyles, 2017).

ESM-based curricula

In an ESM-based curriculum, students explore and learn about scientific phenomena using ESMs. ESM-based curricula engage students in actively constructing knowledge in a computational microworld using scientific inquiry practices similar to those scientists use to construct knowledge about the real world. The computational microworlds are designed on the basis of current fundamental scientific paradigms (Kuhn, 2012). Every agent-level entity in the microworld follows the rules that are specified according to the current scientific principles. Also, emergent patterns are consistent with scientific understanding.

GenEvo – An ESM-based curriculum

The GenEvo curriculum incorporates a series of computational models designed using NetLogo (Dabholkar & Wilensky, 2016). NetLogo is an agent-based modelling software that has been used for research work regarding emergent systems as well as to design educational curricular units (Wilensky, 1999).

Figure 1: A student exploring intracellular molecular interactions in an ESM of a bacterial cell

In this curriculum, students are first presented with a computational model of a bacterial cell with a genetic circuit in which certain components such as proteins and parts of DNA interact in a specific manner. Students explore and play with the model to figure out these interactions and how they result in complex emergent behaviour at the cellular level. In the next two subunits, students explore and tinker with the models of genetic drift and natural selection. They observe competition between cells and reason about emergent patterns at the population level. Finally, students revisit the first model and engineer the genetic circuit to make their cells ‘fitter’ to reproduce. The cells where genetic circuits are designed by the students then ‘compete for survival’ in a limited resource environment.

All of the computational models in the GenEvo curriculum are designed using the agent-based perspective of modelling emergent systems. In each model, the agents and their behaviours at the micro-level are computationally coded. As agents interact with each other and with their environment, it results in emergent patterns at the macro-level (Wilensky & Resnick, 1999; Wilensky, 1999b). Students can observe both the interactions at the agent-level and patterns at the system-level. In this curricular unit, the emergent properties of biological systems include genetic regulation, carrying capacity, genetic drift and natural selection. Students work in small groups of two or three. Their explorations are scaffolded by guiding them to focus on specific aspects of agent behaviours, such as resource availability or DNA-proteins interactions. Students are asked to explore a model and identify its aspect that they find interesting to investigate. They are asked to state it as a research question and state their preliminary answer as a testable hypothesis. Then they design and conduct computational experiments in the ESM learning environment to test their hypotheses and present their investigations. Their findings collectively build towards ideas about the emergent properties regarding genetic regulation and evolution.

ESM-mediated Expansive Learning

We view ESM-mediated students' learning as expansive learning to understand the affordances of ESM-based curricula for mediating students' engagement with disciplinary ideas in the classroom community (Engeström, 2001) (Figure 2). Expansive learning is viewed in the context of an activity system, which includes tool and sign that mediate the relationship between a subject and an object, rules, community and division of labour (Figure 2a). Expansive learning produces culturally new patterns of activity.

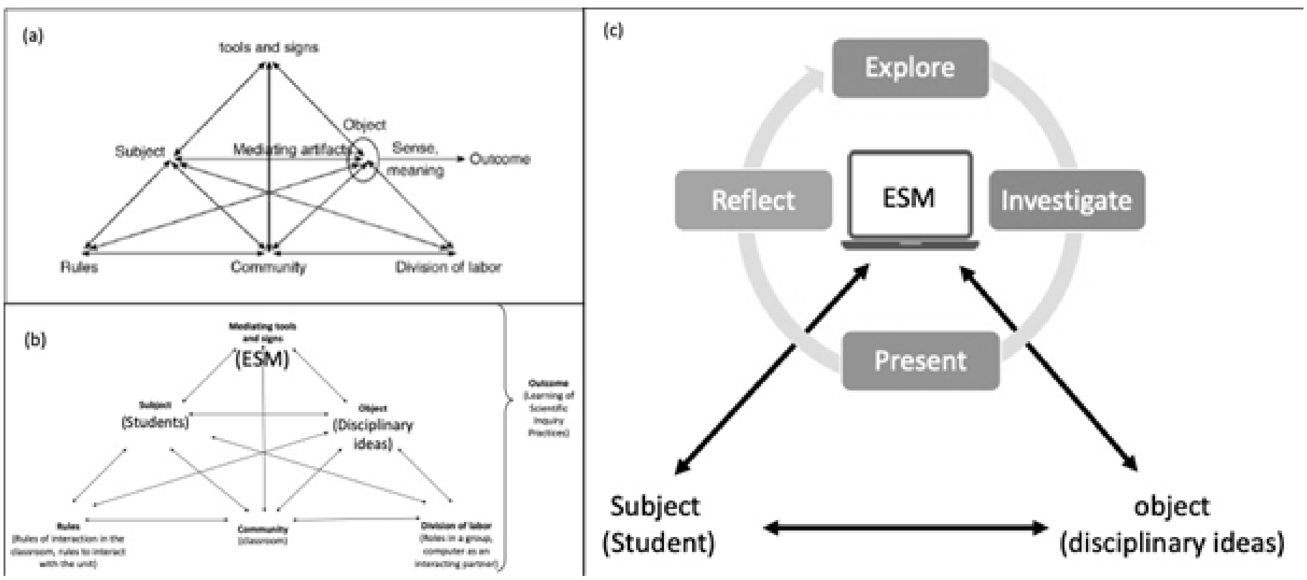

Figure 2: An ESM-mediated activity system (a) A second generation activity system that takes into account learning in the context of a community (Engeström, 2001) (b) ESM-mediation in an activity system in a classroom context (c) Various forms of student engagement with ESM.

In most classroom settings, the relation between the subjects (students) and the objects (disciplinary ideas) is viewed as students understanding the scientific knowledge that is provided to them by teachers and textbooks. Whereas, we expect that a computer-based ESM can potentially mediate students' expansive learning such that it would transform their relationship with disciplinary ideas. Our research question is as follows:

How does the design of ESM-based curricula mediate transformation of the relationship between the students and disciplinary ideas as they collaboratively construct knowledge?

METHODS

Research context

The data used in this paper is from a computational biology course that included the GenEvo curriculum. The first author of this paper was the lead-designer of the ESM and the curricular unit, and the lead-facilitator in these implementations. We use the data from the fourth iteration of the course. The first two iterations were in a weekend extra-school program for middle school students conducted by a talent-development centre in a mid-western university in the United States. The latter two implementations were in residential summer camps in a western city in India where students from all over India participated. The students that participated in both these programs were of age 11 to 14. In the fourth iteration of this design-based implementation research, 12 students participated of whom 5 were females, and 7 were males. All the students were of Asian Indian origin.

Data collection and analysis

We collected data in various forms, namely, extensive field notes by a field researcher in the class, videos of student discussions, workbooks in which students wrote their observations and explanations, the computational artefacts (models, screenshots and presentations). We also conducted pre- and post-tests, and pre- and post-interviews about their ideas regarding science learning and what scientists do. In the sections that follow, we use video data and data from pre- and post- interviews. We focus on interview questions that are about students' perceptions regarding the learning of science, especially from the perspective of understanding their agency in knowledge construction, and practices that scientists follow to construct knowledge. The question prompts were: *(1) Choose any topic that you learned in your science class/ in this course and explain how you learned it; (2) What do you think scientists do as their daily work?; (3) So, scientists construct knowledge about the world, right? How do they do that? How do they know that what they have figured out is right?* We used mixed-methods analysis to investigate how students talk about science learning and practices of scientists. The bottom-up, open coding was done using the constant comparative method (Glasser & Strauss, 2017). All the student responses were then coded by two researchers. Each student response was coded once for every category. The disagreements between the researchers were discussed and resolved until Cohen's Kappa value was greater than 0.7 for each category.

ANALYSIS

ESM-mediated expansive learning

In this section, we share our findings about how certain design features of ESM, specifically agent-based representations and constructionist design in the form of a microworld, fostered students collaborative expansive learning in a classroom context. In the GenEvo course, students worked in small groups. Each group constructed their contextual knowledge through their own investigations in the context of the ESM (Figure 2c). They identified their research questions, designed and performed experiments, and collected evidence. They presented their findings to the class. Other groups in the class questioned them, to seek clarifications and to provide counter-evidence that they may have found through their own investigations. Students iteratively went through this cycle of exploration, investigation, presentation and reflection (Figure 2c). Students were asked to give credit to other groups if they wanted to build on the ideas that were proposed and investigated by other groups. This is similar to how a scientific community cites works of other research groups to build collective knowledge.

Agent-based representations

An ESM provides agent-based representations to reason about emergent patterns in the case of a natural phenomenon. Such restructurations of emergent phenomena with dynamic computational representations improve the learnability of these complex ideas (Wilensky & Papert, 2010). The simplicity of these behavioural representations mediated students' sharing of ideas and allowed them to collaboratively figure out mechanisms of emergent patterns. When Vidya (pseudonym[1]), a rising 8th-grade student in India, was asked how she learned in the GenEvo course, she responded as follow:

> "(I learned) the cell's way of regulating production of specific proteins that are needed because they eat up some energy. Because every protein has its cost, so a cell has to know when it is necessary to make it and not just make it when it's not needed….. Because, it also degrades, so it's of no use….. So, the cell's way of doing that is to produce LacI, which is.... when there is no lactose, it can join with the DNA and it can prevent the formation of LacY and LacZ by RNAP, but when there is lactose, it is unable to do so, because it is blocked by the presence of lactose. (I learned it) by piecing something together. It just came to me, I guess! Before that we were discussing, the LacI and lactose binding thing…. I was wondering why this happened. And then *Sajid* (her partner) found out that when LacI is bound, the RNAP doesn't roll. Then I just thought of it." (Vidya's interview, May 2018)

What Vidya explained is how she learned an advanced emergent phenomenon of molecular genetic regulation. She did this by observing interactions of DNA and proteins as computational agents in the model by herself and building off of her partner's ideas. What Vidya is describing as *'the cell's way'* is an emergent phenomenon that manifests at the cellular-level because of biochemically constrained stochastic molecular interactions. In the conversation above, Vidya's use of *'the cell's way'* is a reference to emergent cellular behaviour from a class discussion. This had become a highly debated topic of discussion in the class, when Vidya explained to the rest, how these *random interactions* would result in emergent sensory behaviour of a cell.

Constructionist design

In the GenEvo course, the students learned emergent ideas by manipulating behaviours of computational agents and investigating system-level effects of those manipulations manifested in the microworld. Since every student used the same microworld, they developed a shared language to talk about those computational objects. These agent-level representations were 'object-to-think-with', which allowed students to collectively reason about emergent properties (Papert, 1980). This is how Sajid, Vidya's partner, investigated computational representations of proteins as objects-to-think-with to reason about a cellular behaviour.

"I was observing (potato-shaped things). So first I observed that it was just random movement. Then I saw that it was going on a straight line (on DNA), so I saw that it was rolling along the DNA. And then suddenly, when it went off pink triangles and rectangles were produced. I did this experiment 2 or 3 times and then I figured out that the RNAP produced LacZ and LacY…." (Sajid's interview, May 2018)

Sajid made an observation about a pattern that was related to the production of proteins, which were

[1] All the names used in this paper are pseudonyms.

represented as *pink triangles and rectangle*s pertaining to the movement of RNA polymerase (represented as a *potato-shaped thing*). He hypothesised that the movement of RNA polymerase on DNA is related to protein production. He verified it by repeating the experiment a few times under the same conditions. His carefully verified hypothesis become a piece in the puzzle that Vidya used to understand and explain the molecular mechanisms of genetic regulation.

In the GenEvo course, the agent-based restructurations of biological systems enabled students to develop a deep understanding of emergent ideas about genetic regulation and evolution. Traditionally they would have been told about these ideas authoritatively by their teachers using static models or animated videos to remember and then asked to explain those in the exams. Whereas in this course, students developed deep understanding of these ideas through ESM-mediated scientific inquiry. They collaboratively constructed knowledge about those ideas by asking questions, planning and carrying out investigations, analysing and interpreting evidence, and communicating their findings with others.

CONCLUSIONS AND IMPLICATIONS

ESMs and ESM-based curricula are design frameworks for learning environments to engage students in authentic scientific inquiry practices and learning about complex emergent systems phenomena. ESMs mediate students' expansive learning by providing them computational objects-to-collectively-think-with, in the context of a microworld. In the GenEvo course, students performed scientific investigations using these microworlds, shared their findings, argued about those, and developed a deep understanding about disciplinary ideas by engaging meaningfully in authentic scientific inquiry practices. Our analysis of ESM-mediated expansive learning revealed, how agent-based representations and constructionist design principles made ESM-based curricula effective for collaborative knowledge construction in a classroom setting.

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