International Journal of Science Education

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tsed20

Designing computational models as Emergent Systems Microworlds to support epistemically agentive learning of emergent biological phenomena

Sugat Dabholkar & Uri Wilensky

INTERNATIONAL JOURNAL OF SCIENCE EDUCATION
https://doi.org/10.1080/09500693.2024.2356228

Designing computational models as Emergent Systems Microworlds to support epistemically agentive learning of emergent biological phenomena

Sugat Dabholkar[a] and Uri Wilensky[b]

[a]Department of Education, Tufts University, Medford, MA, USA; [b]School of Education and Social Policy, Northwestern University, Evanston, IL, USA

ABSTRACT
To support students' agency in the process of constructing knowledge in a science classroom, it is important to design learning environments that allow students to shape knowledge building practices. In this paper, we present an Emergent Systems Microworld (ESM)-based learning environment called GenEvo, which is designed to 'restructurate' learning of fundamental ideas in modern biology, such as gene regulation. We study how cognitive, social, and affective properties of agent-based restructurations supported student learning. We report findings from a qualitative analysis of video data of student participation and interviews in the fourth iteration of a design-based research project about an ESM-based curricular unit. We discuss how specific design features of the ESM supported students' epistemically agentive learning. Students of the GenEvo course shaped practices to investigate and construct knowledge about emergent biological phenomena and learned about emergent phenomena related to gene regulation and evolution. This work demonstrates how the properties of a restructuration make ESM-based learning environments effective for students to collectively shape knowledge building practices and learn about emergent phenomena.

ARTICLE HISTORY
Received 26 May 2023
Accepted 13 May 2024

KEYWORDS
Agent-based modelling; constructionism; restructurations; epistemic agency

Introduction

Recent science education reforms emphasise engaging in and learning about practices that scientists use to make sense of the world rather than limiting science education to knowing scientifically established ideas (NGSS Lead States, 2013; Schwarz et al., 2017). This shift in science education requires reimagining the roles of students and teachers in the science classroom so that students become *doers of science* and not *receivers of facts* (E. Miller et al., 2018). Doing science in the science classroom means engaging students in science practices to construct disciplinary knowledge. What are science practices that students should engage in? The Next Generation Science Standards (NGSS) has recommended a set of science practices that are epistemically equivalent to the practices of

CONTACT Sugat Dabholkar sugat.dabholkar@tufts.edu Department of Education, Tufts University, Medford, MA, USA

scientists (NGSS Lead States, 2013). However, this framing creates a foundational contradiction for doing science using the NGSS framework (E. Miller et al., 2018). Miller et al. (2018) argue that having a set of practices chosen by others as important to learn and expecting students to mimic those practices does not position students with the power to shape the knowledge production and practices of a community. To position students as epistemic agents in science classrooms teachers relinquishing epistemic and content authority and learning environments need to include features that would allow students to construct, critique, and evaluate claims to collectively build knowledge. In this paper, we present a computational model-based learning environment designed for middle and high school biology students to build knowledge about a modelled phenomenon and study their epistemically agentive learning.

While designing new learning environments, it is also important to incorporate theoretical and methodological advances in different disciplinary domains. There is a significant disparity between how biologists study biological systems and how high school biology students learn about those systems (Wilensky & Reisman, 2006). Other than technical advances in molecular biology, one of the significant shifts in contemporary research in biological sciences is the use of systems theoretical perspectives to understand and investigate biological complexity using computational approaches (Kitano, 2002, 2017). From the molecular level to the cellular level to the organismic level to the ecological level, biological systems can be studied as complex systems comprised of interconnected constituent parts. Agent-based computational models have been demonstrated to be effective in investigating emergent properties of such complex systems (Aslan et al., 2018; Dey et al., 2006; Wilensky, 2020) and teaching emergent biological phenomena related to population dynamics and evolution and student participation in inquiry-based learning (e.g. Wagh et al., 2017).

We posit that a computational model of a biological system that is cognitively accessible for students to formulate and test their ideas can support *doing systems biology* in epistemically agentive ways. There is a long history of using computational models in the science classroom to teach various complex phenomena ranging from emergent properties of matter because of its particulate nature (Levy & Wilensky, 2009) to climate change (Svihla & Linn, 2012; Vitale et al., 2016) to evolution (Wagh & Wilensky, 2018; Wilensky & Novak, 2010). Design features of these models and pedagogical approaches to using them can support or hinder specific forms of participation (Berland & Lee, 2012; Langbeheim & Levy, 2018). Little is known about how specific design features of such computational models can support student participation in knowledge-building practices by positioning them with the epistemic agency. In this paper, we present an Emergent Systems Microworlds (ESM)-based learning environment designed to support students' epistemic agentive learning of emergent biological phenomena. ESMs use agent-based representations which are known to support the learnability of complex systems phenomena and make sense of how system-level aggregate patterns emerge because of agent-level properties and interactions (Wilensky & Papert, 2010; Wilensky, 2020). We study how cognitive, social, and affective properties of agent-based restructuration in the ESM supported students' epistemic agentive learning as they participated in and shaped knowledge-building practices to make sense of emergent phenomena in biology.

Design framework

Emergent Systems Microworlds

Over the years, scientific communities across the globe have developed experimental model systems that have affordances to investigate specific aspects of natural phenomena (Striedter, 2022). For example, fruitflies' (*Drosophila*) chromosomal organisation and their short life span have made them a model system to study genetics. Similarly, the organisation of a small number of neurons in roundworms (*C. elegans*) is beneficial to the study of neurobiology. 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 epistemic agency within the constraints of a classroom. We present Emergent Systems Microworlds (ESMs) as computational model systems for students to investigate a modelled emergent phenomenon.

ESM design combines two design approaches in Learning Sciences, namely agent-based modelling of emergent systems and constructionism (Wilensky, 2001; Papert, 1980). Agent-based representations in ESMs create affordances for learners to engage deeply with emergent phenomena (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 uses an ESM to facilitate such student engagement in self-directed, interest-driven explorations and investigations. Students are encouraged to share their findings and participate in teacher-guided reflections to collaboratively construct knowledge about the modelled emergent phenomena in an ESM.

Our design in this paper builds on the earlier work of using agent-based computational models for learning about emergent phenomena (Arastoopour et al., 2020; Brady et al., 2015; Blikstein & Wilensky, 2005; Levy & Wilensky, 2009; Sengupta & Wilensky, 2009; Stieff & Wilensky, 2003; Wagh & Wilensky, 2018; Wilensky, 2003; Wilensky & Novak, 2010; Wilkerson-Jerde et al., 2015; Wilensky & Rand, 2015). Emergent phenomena are the ones in which uncoordinated interactions between autonomous agents result in emergent patterns at the system level (Wilensky, 2001). The emergent systems perspective is useful for understanding several natural phenomena ranging from prey-predator relationships to nectar collection by honeybees, to the kinetic molecular theory (Danish, 2013; Hmelo-Silver & Azevedo, 2006; Klopfer et al., 2005).

The *microworlds* part of an ESM is inspired by Papert's idea of microworld in his theory of constructionism. The Emergent Systems Microworld (ESM) design framework incorporates the following three key ideas from the constructionist design framework: (a) personally meaningful engagement, (b) construction of public entities, and (c) expression and validation of ideas through computational microworlds. In our conceptualisation of microworlds, we use the functional definition of microworlds (Edwards, 1995). From the functional perspective, microworlds are conceptualised as encapsulated open-ended exploratory learning environments in which a set of ideas can be explored through interactions that lead to knowledge construction (Edwards, 1995, 1997; Hoyles & Noss, 1987; Noss & Hoyles, 2017; Papert, 1980; Roschelle, 1991; Wagh et al., 2017).

ESMs have computational entities which serve as objects-to-think-with in a microworld. Objects-to-think-with is a design concept in Constructionism (Papert, 1980; Turkle, 2007). In a constructionist microworld, these are computational objects that can be manipulated and observed to think about various ideas related to the behaviours of objects, their interactions, and patterns that are generated through those behaviours and interactions. As learners use these objects to make sense of a phenomenon they are investigating, their engagement becomes meaningful to them in the context of the investigation. Another idea that is central to the constructionist design and pedagogical principles is consciously engaging learners in constructing a public entity. Papert and Harel (1991) have famously given examples of such public entities as a sandcastle on the beach or a theory of the universe (Papert & Harel, 1991). In the ESM-based GenEvo learning environment, students are asked to construct public entities for the classroom audience. These are the evidence-based claims that they develop and test by conducting computational experiments using the ESM. They iteratively formulate and validate their claims using the ESM to collectively build knowledge of disciplinary ideas related to the modelled phenomena.

The ESM that we present in this paper is designed using NetLogo (Wilensky, 1999), an agent-based modelling platform that hosts hundreds of microworlds in different domain areas which have been developed to model emergent patterns for research as well as educational purposes. Several curricula that use NetLogo have been demonstrated to be effective for student learning in various disciplinary domains ranging from population dynamics (Wilkerson-Jerde et al., 2015) to material science (Blikstein & Wilensky, 2005) to *Eco-Systemic* thinking (Gkiolmas et al., 2013).

Theoretical frameworks

Restructuration

The underlying theoretical framework in the design of ESM-based learning environments is based on the idea of restructuration (Wilensky & Papert, 2010; Wilensky, 2020). Structuration is the encoding of knowledge in a domain, which is largely influenced by available representational infrastructure that can be used to express the knowledge. The representational infrastructure used to express knowledge in a domain also influences the learnability of the knowledge. For example, Hindu-Arabic (0, 1, 2, 3, ..) and Roman (I, II, III, IV, …) numerals are representational infrastructures that support structurations in arithmetic. Arithmetic operations such as multiplication and division underwent a huge change because of the restructuration from Roman to Hindu-Arabic numerals. The effectiveness of a representational infrastructure would result in a structuration being replaced by another structuration. This process of change as well as the new structuration are referred to as restructuration. Properties of a restructuration influence the learnability of disciplinary ideas, especially from the point of view of democratising access to powerful ideas to the wider and younger population (Wilensky, 2020). Five fundamental properties of a restructuration, namely, power properties, cognitive properties, affective properties, social properties, and diversity properties can influence the effectiveness of the restructuration.

The cognitive properties are about the ease of learning the knowledge domain. For example, to compare the cognitive properties of Hindu-Arabic and Roman number systems, one needs to compare the cognitive ease of learning operations such as multiplication with each of the structurations. The social properties are about the ease of sharing newly established or developing ideas as *knowledge products* in a domain. This requires a structuration that is effective in supporting the expression of ideas in ways that make the ideas easily sharable and usable for others. A restructuration can make the knowledge more or less engaging. The likability of domain knowledge can be influenced by the structurations that are used to engage with the domain knowledge (Wilensky, 2020). Affective properties of a structuration can improve its *playfulness* which is important from the perspective of engaging students in investigating and learning ideas in a disciplinary domain.

Epistemic agency and epistemically agentive learning

The epistemic agency is an important theoretical construct to consider for supporting student engagement in *doing science*. 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 (E. Miller et al., 2018; Scardamalia & Bereiter, 1991; Stroupe, 2014). We see epistemic agency being dynamic and interactionally constructed as students propose and evaluate their ideas, and make decisions about what they already know, what they want to know, and how they want to figure that out (Keifert et al., 2018; Ko & Krist, 2019; Krist et al., 2023; Stroupe, 2014). To truly support such agency in a classroom, learning environments need to allow students to evaluate knowledge products that they create and shape knowledge-building practices.

In this paper, we use a related and equally important construct, epistemically agentive learning which focuses on student learning as they exercise their epistemic agency. Supporting epistemic agency is pedagogical (Krist et al., 2023), which is about teachers supporting students' ideas and decisions related sensemaking of a phenomenon they are investigating, whereas epistemically agentive learning is about learning disciplinary ideas and practices as students exercise their epistemic agency. To support epistemically agentive learning the learning environment needs to provide ways for students to formulate and evaluate knowledge claims that are central to understanding the phenomenon they are investigating.

We argue that agent-based representations in an ESM serve the purpose of supporting students' epistemically agentive learning of complex emergent phenomena. The restructuration properties of agent-based representations provide cognitive access to collectively build knowledge in a playful manner. In this paper, we analyse how cognitive, affective, and social properties of the agent-based restructuration in an ESM mediate students' learning of emergent aspects of gene regulation and evolution in a biology classroom. We investigate the following research question:

> How did restructuration properties of an ESM support epistemically agentive learning of emergent biological phenomena?

Research context

GenEvo ESM – restructuration of genetics and evolution

To engage students in constructing knowledge of disciplinary ideas regarding gene-regulatory mechanisms and evolution, we created an ESM-based curriculum, GenEvo

(Dabholkar & Wilensky, 2016; Dabholkar et al., 2018). This curriculum incorporates a series of four related computational models designed using the software NetLogo. Since these four NetLogo models are strongly related, they form an ESM because the underlying rules for agent behaviour are consistent across the models. These models are about the focal phenomena in the unit, which are gene regulation in Lac Operon and microevolutionary changes in bacterial population under different environmental conditions because of genetic drift and natural selection (See Figure 1). These rules for agent behaviour (such as a protein LacI binding to a specific region of DNA) are based on established ideas in molecular genetics (Müller-Hill, 1996) and evolutionary biology (K. Miller & Levin, 2010). Using this curriculum, students can investigate various emergent biological phenomena, including gene regulation, carrying capacity, genetic drift, and natural selection (Models A, B, and C in Figure 1). Students can also design a genetic circuit inside a cell and test the selective advantage in a limited resource environment (Model D in Figure 1). In this paper, we focus our analysis on the Genetic Switch model (Figure 1(A)) (Dabholkar et al., 2020) which is about gene regulation in a bacterial cell.

GenEvo curriculum

The GenEvo curriculum is designed for students to learn about fundamental ideas in modern biology (Dabholkar & Wilensky, 2016). They learn about regulation gene expression in bacterial cells in response to environmental conditions through molecular interactions between genes and proteins. They study about how populations evolve in

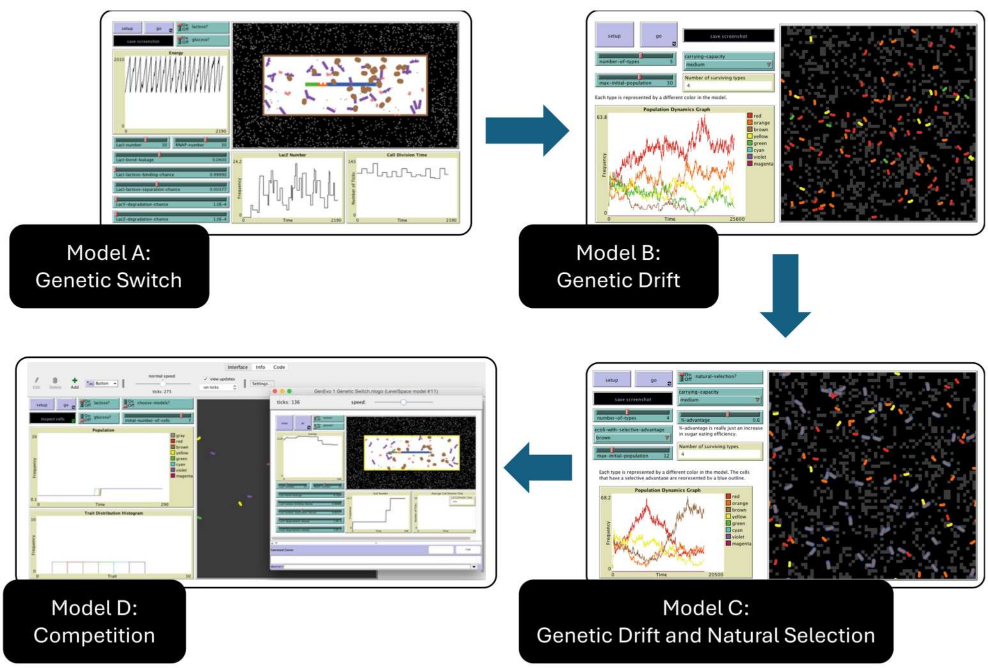

Figure 1. Four NetLogo models in the GenEvo ESM designed to support manipulations and observations of biological phenomena at molecular, cellular, and ecological levels.

nature under different environmental conditions. They learn about mechanisms of microevolution by investigating phenomena related to natural selection and genetic drift and how those result in evolutionary changes at the short time scales.

The GenEvo 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 as evidence for a particular claim? What are various ways to collect, analyse 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 of the biological system under investigation that were foregrounded in the ESM design. Throughout the curriculum, students iteratively explored specific aspects of various phenomena related to gene regulation and evolution, investigated specific questions, collected evidence, and presented how their evidence supported their claims regarding their own research questions (Figure 2).

The pedagogical approach used in all the GenEvo courses is shown in Figure 2. Students first explore a model and talk about the observations that they find interesting. Students' investigations are scaffolded by guiding them to focus on specific aspects of agent behaviours such as sugar availability or DNA-proteins interactions. The primary observations often help students in identifying aspects of the system that they would find interesting to investigate. They are asked to formulate research questions that they want to investigate 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 learning about the emergent aspects of gene regulation and evolution. They are asked to present their findings to the class and answer the questions that the class has about their works. Finally, the class participates in a discussion to decide what claims are established and what they would like to know more about. Then, the class

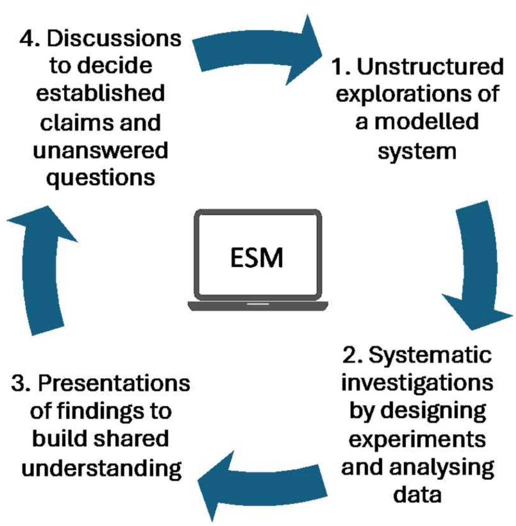

Figure 2. Pedagogical approach for an ESM-based curriculum.

uses the same model in an unstructured manner to explore those aspects. If most of the questions are answered and unanswered questions cannot be answered using the model, then the class moves on to the next model.

Participants and setting

We conducted GenEvo courses in four locations: first two times during a weekend extra-school programme for middle school students conducted by a talent-development centre in a midwestern university in the United States, and then twice in residential summer camps in a western city in India where students from all over the country participated. The first author, an Indian researcher who did PhD in the United States, was the lead teacher in all these courses. The author was also the lead designer of the computational models and the curriculum. The computational models and the course content was modified after each iteration.

In this paper, we present a qualitative analysis of the fourth iteration of the course. In the fourth iteration, the course was conducted in India for two weeks. All the participating students were of Asian Indian origin, five students identified as females, and seven identified as males. The course was divided into four modules – (a) Genetic Switch, (b) Genetic Drift, (c) Genetic Drift and Natural Selection, and (d) Designing Genetic Circuits. Each module introduced students to the interface of the associated computational models and had prompts for students to design and conduct their investigations to study the aspects of the ESM they found interesting. Students worked in groups of two. The groups were asked to collect evidence to support their claims. The evidence collected by students ranged from taking a screenshot to creating a table of multiple trials of multiple conditions. Student groups presented their claims and evidence to the class. The audience asked questions that led to discussions about evidence, methods of collecting evidence, and the reliability of those.

Students used the four computational models in the GenEvo ESM (Figure 1) sequentially to investigate various emergent biological phenomena related to gene regulation in a bacterial cell and genetic drift and natural selection in a population of bacteria. Since all students used the same models but studied different aspects of the modelled phenomena, they collectively built an understanding of how gene regulation, genetic drift, and natural selection work.

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-tests and post-tests, and pre-interviews and post-interviews. The fieldnotes and recordings were collected by two research assistants.

Methods

To investigate students' epistemically agentive learning with the ESM-based curriculum, we conducted a qualitative analysis (Small, 2011) of the fourth enactment of the GenEvo curriculum that took place in India. We analysed student interviews before and after they participated in the course, and we analysed video data of student participation in the course.

Qualitative analysis of student interviews

We first analysed videos of students' pre-interviews and post-interviews to identify how students perceived their participation and learning in the GenEvo course in comparison with their perceptions of science learning in their regular school settings. We constructed coding categories for student utterances that were about their role in the classroom and their agency using the bottom-up, open coding approach with the constant comparative method (Glaser & Strauss, 2017) (Table 1). All the student responses were then coded by two researchers. Any disagreements between the researchers were discussed and resolved until Cohen's Kappa value was greater than 0.7 for each category.

Qualitative analysis of student participation

To further study how restructuration properties of the ESM supported students' epistemically agentive learning we used micro-ethnographic methods to analyse their classroom participation (Erickson, 1986, 2010), focusing on the dynamics of shifts in students' involvement in the learning activities and their shaping of practices of knowledge construction and evaluation in the classroom. Using a top-down approach, we identified all the instances in the field notes in which there was a class discussion about making and establishing knowledge claims through observations and investigations.

For example, the following section in the field notes is coded positive for a class discussion about making and establishing knowledge claims through observations and investigations:

Table 1. A coding scheme for student interviews.

Code description		Exemplar Coded Response
Teacher led: A student talking about their learning of science being directed by a teacher		[the teacher] kind of just described everything to us and then she had a ppt and then she recited notes for us to write
Student choice/control: A student talking about having an active choice or control about their classroom participation		[the teacher] gave us no answers, so we all had to think for ourselves, experiment ourselves.
Collective Learning: A student talking about classroom community being engaged collectively in knowledge construction		We even showed evidence and all. If someone disagreed, they could argue, in a good way and even like show their proof to not support my opinion and all
Participation in Practice of science	**Asking questions:** A student talking about asking questions about unknown natural phenomena	When we were asking questions about 'what is what' you were not answering us. And then we came to answer our own question by observing the model so well that … .
	Conducting investigations: A student talking about performing investigations to observe effects of a change/ manipulation	We learned about what were in the bacteria by changing parameters and figuring out for ourselves.
	Testing claims: A student talking about testing preliminary claims about observed patterns	We figured out that, LacZ was the triangle, when we saw that LacZ graph go up, every time the triangles were made up by RNAP rolling over the DNA and we did that by reducing LacY degradation chance and increasing it and increasing and decreasing LacZ degradation chance and through that we came to the conclusion that LacZ is the pink triangles.'
	Sharing ideas: A student talking about sharing newly established ideas or observations with others in the class	'we came to know what function was happening to form a protein … we showed powerpoints to prove our points. We even showed evidence and all.'

> Sagar tries to answer the questions by talking about a fluctuating relationship, to which Shaurin disagrees. [The teacher] places both these opinions before the class and asks them if they have supporting evidence for their points. Shaurin comes to the front of the class to show his evidence so that everyone can have a look. [The teacher] ties that back by saying that we are trying to understand how to use evidence for argument. Mohan meanwhile has different evidence for this. Meera points out that the conditions of the experiment are different in Shaurin's case and [The teacher] asks whether with the exact same parameters, the same results will be observed in the model or not.
>
> (Fieldnotes, May 15, 2018)

This episode is about students' arguments regarding a claim about relationships in the ESM and experimental conditions used to establish the relationship. All these episodes related to knowledge construction and evaluation (92 episodes) were further analysed using a bottom-up coding approach to identify the intended goal of the learning activity, design features of the ESM, and accompanying ESM-enabled pedagogical moves. With this approach, we identified the episodes in which the design features of the ESM supported students in shaping practices to construct, evaluate, and establish claims. For example, the micro-ethnographic analysis of the episode presented above revealed that students were trying to compare the energy of the cell under different conditions to establish a pattern regarding the changes in the energy of the cell and how different features of the ESM about setting specific experimental conditions and recording evidence based on an experimental trial enabled making and sharing these comparisons. This analysis helped in identifying and investigating specific design features connected with the restructuration properties of the ESM and how they supported students' epistemically agentive learning. Based on the micro-ethnographic analysis of videos, student artifacts, and responses from students' post-interviews we constructed vignettes to illustrate how restructuration properties of supported students' epistemically agentive learning (Erickson, 1986; Small, 2011).

Results

We first present an analysis students' pre-interviews and post-interviews to discuss how they perceived shifts in their participation in a science classroom, specifically regarding their role and epistemic agency. Then we discuss vignettes based on analysis of students' classroom participation and interviews that illustrate how different features of the ESM and ESM-based curriculum supported students' epistemically agentive learning.

Students' perceptions of their epistemic agency

The comparison of pre-interview and post-interview responses to identical question prompts about science learning revealed a shift in how students viewed their participation in a regular science classroom and the ESM-based learning environment (Figure 3). In this analysis, we focus on how students perceived their epistemic agency in connection to their learning.

When asked about their past learning experiences in science classrooms, students viewed science learning as a teacher-led process, and they did not see themselves in positions of having active choice and control in a classroom (first two columns in Figure 3).

When talking about their participation in the ESM-based GenEvo curriculum, all of the twelve interviewed students talked about having had an active choice and control in the process of learning. Several students in their post interviews talked about (last five columns in Figure 3) about their participation involving collective learning by asking questions, conducting investigation, testing claims and sharing ideas.

The following response illustrates how a student viewed his learning in the GenEvo course as a collective and epistemically agentive learning experience:

> I learned like a scientist mostly because [the teacher] didn't tell us anything. [The teacher] gave us no answers so we all had to think for ourselves, experiment ourselves, and then we got to know how scientists do it because they don't have the answers.
>
> [An excerpt from a post-interview with Sagar, May 2018]

Sagar compared his learning in the course to the learning of a scientist. He talked about his participation in *thinking* and *experimenting*. The use of the first-person plural pronoun *we* by the student indicates that he was talking about collective participation in the process of establishing knowledge of not only disciplinary ideas but also of science practice – 'we got to know how scientists do it'.

Another student, Zahir, talked about their participation as a group in specific practices such as making observations and sharing ideas to make sense of the biological phenomenon of protein production to collectively figure out answers to their questions:

> When we were asking questions about what [the teacher] was not answering us. And then we came to answer our own question by observing the model so well that … each and every one of us was thinking about it in the breaks and all. We came to know what function was happening to form a protein … we showed powerpoints to prove our points. We even showed evidence and all.
>
> [An excerpt from post-interview with Zahir, May 2018]

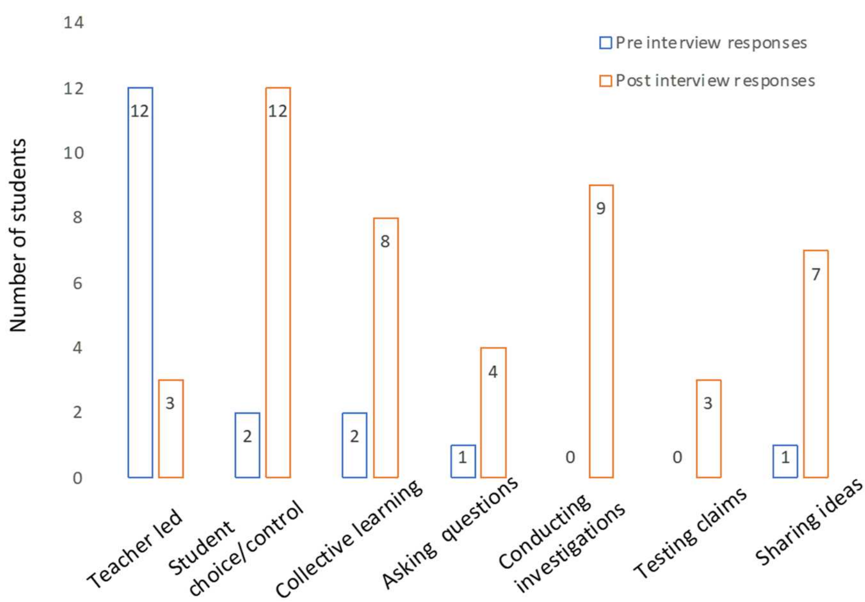

Figure 3. Students' perceptions about their participation in learning of science in a classroom.

These student responses also indicate how they saw a shift in epistemic and content authority in the ESM-based classroom. Student's expectation of a teacher being an authority to answer a question changed to exercising their epistemic authority by using *the model* (ESM) which served as a system to construct and test their claims. Similar to the previous student, this student also talked about how *they came to know* about a disciplinary idea of regulation of protein production that was modelled in the ESM. These excerpts show how students perceived to be positioned with epistemic agency and how ESMs allowed them to exercise their agency to learn about the modelled emergent biological phenomena.

In the following part, we present a micro-ethnographic analysis of student participation and post-interview responses to illustrate how cognitive, social and affective properties of the GenEvo ESM supported students' epistemic agency in shaping practices to build knowledge about emergent phenomena.

Cognitive and social properties of restructuration in GenEvo

A crucial aspect of positioning students with epistemic agency is to design opportunities for students to be in charge of making decisions about how to build knowledge about a phenomenon under investigation (E. Miller et al., 2018). The cognitive properties of the agent-based restructuration allow learners to observe micro-level behaviours and interactions as well as macro-level patterns. For example, in the GenEvo ESM students could observe DNA–protein interactions, and macro-level patterns, such as stimulus-based regulation of protein production. Whereas the social properties of restructuration support collective knowledge construction through easy sharing, evaluation, and incorporation of ideas.

A. Shaping data analysis practices

The following vignette illustrates how cognitive and social properties of the ESM supported students in shaping data collection practices to carefully evaluate evidence. On the first day of the course, students explored a computational model of a cell and shared their observations regarding proteins, DNA regions, environmental conditions (availability of sugar), and the energy of the cell. On the second day, the teacher asked them to systematically investigate specific aspects of the model and to collect evidence to support their claims. In this session, students argued about the validity of their claims and observations using evidence that they collected (Figure 4). Most of the student groups recorded evidence by taking screenshots of the model. The remaining groups only verbally recorded their evidence.

The student groups were asked to make observations and formulate evidence-based claims about changes in the energy of the cell in different environmental conditions. The differences in the environmental conditions were because of the presence or the absence of sugars in the environment of bacterial cells. There were two sugars in the model, glucose, and lactose. That made four environmental conditions possible regarding sugar availability: no sugar, only glucose, only lactose, and both glucose and lactose.

A student group shared their observations regarding *cell division time* when both types of sugar – glucose, and lactose, were present. Mitali, a member of that group, said that the cell division time was 108 ticks. A tick is a time unit in the model. Mitali's partner Manav

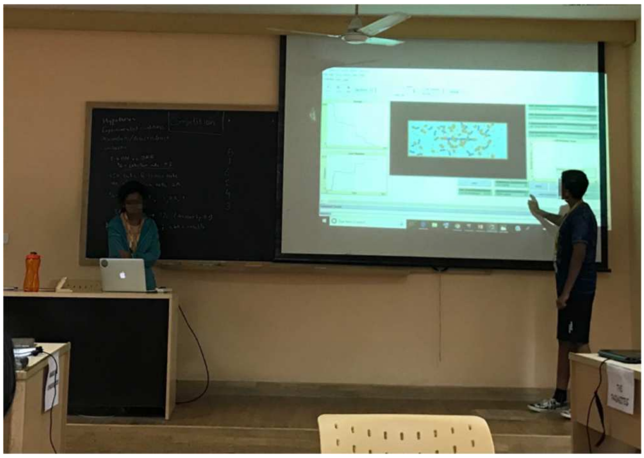

Figure 4. Two students explaining their evidence using a screenshot of the Genetic Switch model.

corrected her and said it was between 105 and 115 ticks. This generated a debate in the classroom. Each group reported a different number of ticks for the same environmental conductions. To resolve the issue, the teacher asked all the groups to perform the same experiment and record their results on the blackboard. The students noticed that the number of ticks was different during each experimental run even when the same environmental conditions were not changed.

The teacher then asked the groups to conduct new experiments for different environmental conditions by changing the sugar availability. The teacher recorded those numbers on the blackboard. Though there was variation among the cell division times for a particular condition, the differences across the conditions were quite large. When the teacher asked students to interpret the data, Shaurin said, 'Even with the same parameters, you won't get the same results every single time … But there is some pattern'. When asked further about the pattern, Shaurin, and other students added that the cell division time is shorter when glucose is present.

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. The ESM was designed specifically to have such variability in data to reflect how these molecules behave in nature. The behaviour of these molecules was modelled to be stochastic. Despite such stochasticity in agent behaviours, there are consistent emergent patterns at the system level. For example, behaviour of proteins that regulate the production of energy-generating proteins is stochastic. Behaviour of energy-generating proteins is stochastic as well. Cell-division time is a system-level property for a cell. Despite stochasticity in protein behaviour, the cell-division time on an average is more for the lactose condition than that for the glucose condition. With a well-designed experimental setup, one can establish such patterns through careful collection and evaluation of evidence.

The classroom community shaped experimenting and data collection practices to compare variations and identify a robust pattern. Later in the class, during a discussion about collecting evidence, a student suggested *creating a table* as a new approach for collecting evidence as opposed to taking a screenshot as evidence, which indicates a shift

Figure 5. Two students conducting experiments and recording data to gather evidence.

from supporting a claim using a single observation to systematically establishing a claim by collecting and analysing data of multiple trials. Over the next couple of days more and more student groups adopted *making a table* of multiple experimental trials as an evidence-gathering practice (Figure 5).

B. Shaping naming-practices to share ideas

In the GenEvo class, as students shaped data practices for careful evaluation of evidence, they also developed shared vocabularies, such as naming computational agents as *potato-shaped things* and *pink triangles* to talk about biomolecules and their interactions inside a cell. This vocabulary evolved from *pink and purple stuff* to *pink triangles*, *pink rectangles*, *purple keys*, and so on. The *pink triangles* and *rectangles* in the models are proteins whose scientific names as LacY and LacZ. The computational objects in a constructionist microworld, such as proteins and regions of DNA are intended to serve as objects-to-think-with (Papert, 1980; Turkle, 2007), which students can manipulate and investigate. To share their findings in ways that made sense to others, students needed to name these computational agents in the model. For this, students arrived at a shared language and used it to establish the properties and functions of the agents. The representational features (the shapes and colours of these objects) were chosen by students for easy identification and description. They used the shared language to describe the behaviours and functions of these agents which were based on the established ideas of molecular genetics. For example, Samir made the following observation to establish that the *potato-shaped things* inside the cells were special proteins, called RNA polymerases (RNAP), which moved on DNA to make other proteins.

> I was observing [potato-shaped things]. So first I observed that it was just random movement. Then I saw that it was going in 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 (potato-shaped things) produced LacZ (pink triangles) and LacY (rectangles) and when one RNAP rolls it produced 5 LacZs, from the graph I figured out.
>
> [An excerpt from a post-interview with Samir, May 2018]

In his response to a question in the post-interview, Samir described how he learned about the function of a protein called RNA polymerase. Using the ESM, Samir investigated the movement of RNA polymerase, represented as a *potato-shaped thing*. He observed a pattern that was related to the production of other proteins, which were represented as pink triangles and rectangles. Samir hypothesised that the movement of RNA polymerase on DNA is related to protein production. He repeated the experiment a few times under the same conditions to establish his claim about the behaviours of agents. When Samir started talking about his observation of the phenomenon of protein production, he mentioned pink triangles and rectangles. When talking about the role of RNAP in protein production, Samir seamlessly transitioned to their scientific names, LacY and LacZ.

C. Shaping micro–macro reasoning practices

One of the core aspects of the GenEvo course is about understanding how and why cells regulate the production of certain proteins depending on the environmental conditions. In order to reason about emergent patterns, thinking in levels is important (Wilensky & Resnick, 1999). Thinking in levels means understanding how micro-level interactions result in the generation of specific patterns or outcomes at the macro-level. In the Genetic Switch model of the GenEvo course, the micro-level is the molecular level, and the macro-level is the cellular level. Production of proteins requires energy, so from an evolutionary perspective, it makes sense to produce proteins only when they are required in a particular environmental condition. The system of gene regulation modelled in the ESM (lac operon) is evolved to regulate the production of proteins required for taking lactose (a type of sugar) into a cell and digesting it to produce energy. These proteins are produced only when lactose is the most preferred energy source in the environment. Using the Genetic Switch model in the ESM-based curriculum, students could simultaneously observe changes at the intracellular interactions (micro-level) between protein, molecular, and DNA regions as well as the cellular level (macro), such as the energy of the cell and cell division time.

Vidya's response to the post-interview question is an example of what we call micro–macro reasoning practice to explain emergent patterns:

> (I learned) the cell's way of regulating the 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
>
> [An excerpt from a post-interview with Vidya, May 2018]

Vidya first talked about *proteins eating up some energy* of a cell, which is a macro-level property of the system. In the GenEvo model, the energy of a cell is modelled as an emergent property of a cell that is dependent on the consumption of sugar in the environment. Specific proteins are required to be produced for the consumption of specific sugars. For example, LacY and LacZ proteins are required for a cell to consume the sugar lactose. Vidya then talked about proteins LacI, LacY, LacZ, and RNAP to explain micro-level interactions in a highly advanced emergent phenomenon of molecular mechanism to regulate gene expression, which is difficult to understand even at the undergraduate level (Duncan, 2007).

What Vidya explained is how interactions between specific biomolecules inside a cell regulate the production of proteins and why that is important from the cell's perspective. Students made observations about micro-level (biomolecules) behaviours and macro-level (cell) patterns, they manipulated agent properties and behaviours at micro-level and environmental conditions (such as sugar availability) to study how that affected macro-level patterns. Vidya and her partner Samir were investigating how the interactions between the biomolecules and sugars (LacI, lactose, RNAP, DNA, etc.) regulate protein production and energy of a cell.

> (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 Samir found out that when LacI is bound (to DNA), the RNAP doesn't roll. Then I just thought of it.
>
> [An excerpt from a post-interview with Vidya, May 2018]

Vidya used a critical piece from Samir's observation about a protein (LacI) binding to DNA and preventing another protein (RNAP) from making different proteins (LacY and LacZ). This practice of making observations and manipulations at the micro-level and linking those to macro-level patterns is a very important aspect of *systems biology* (Kitano, 2002).

Affective properties of restructuration in GenEvo

The likability of domain knowledge can be influenced by structurations that are used to engage with the domain knowledge. The agent-based restructuration in the GenEvo microworld made learning of complex ideas in modern biology playful and enjoyable for students. For example, Pradeep responded as follows, when asked about his learning experience in the GevEvo course:

> We got to play around with the bacterial cell. [the teacher] on the first day didn't help us at all. [the teacher] gave us the model and said to figure out and think what you can. Then slowly we started to get answers. Then [the teacher] helped us connect our thoughts. That's how we discovered what is what in that model.
>
> [An excerpt from a post-interview with Pradeep, May-2018]

Pradeep described his experience of learning as a *playful* experience. He also talked about how playing around helped students in getting answers. Pradeep initially felt not being helped (through direct answers by a teacher) and was compelled to figure out answers using the ESM. Pradeep talked about the pedagogical practice of asking students to share and collectively synthesise knowledge by *connecting thoughts* to *discover* modelled biological processes in the model. This response also indicates how the ESM enabled the pedagogical approach of encouraging students to conduct self-driven investigations to collectively construct knowledge.

When Meera was asked about her learning experience in the GenEvo course, she said the following:

> I learned it by [in a] very interesting way. You don't get to learn like that anywhere. We were ourselves trying to do experiments, and we ourselves were trying to see what would happen if the cell lived in [a] certain kind of environment. I tried to play with the cell. I tried different environments, that's how I found out about things.
>
> [An excerpt from a post-interview with Vidya, May-2018]

Meera talked about her learning happening in a *very interesting way*. Her response indicates that varying experimental conditions in the ESM and learning about the system by conducting computational experiments were interesting to her. Meera, like Pradeep, described her learning experience as being a playful experience. This perception of manipulating agent behaviours and environments to observe the effects and learn about the phenomenon of being playful is indicative of the affective properties of agent-based restructurations in the ESM making learning interesting for her.

Discussion

Socially constructing disciplinary knowledge using science practices is an epistemic process that is centred in educational reforms, including the Next Generation Science Standards (Abd-El-Khalick et al., 2004; Duschl, 2008; NGSS Lead States, 2013). However, it is challenging to support students' epistemic agency such that they construct disciplinary knowledge about not only the core ideas but also shape the disciplinary practices for constructing those ideas (E. Miller et al., 2018; Russ & Berland, 2019). In many traditional biology classrooms, students are often positioned as *receivers of facts* to listen to disciplinary ideas explained by a teacher using static representations. In contrast, the ESM-based GenEvo curriculum provided students with an interactive experimental system that included agent-based representations and constructionist design features to position them as *doers of systems biology*.

Our analysis of student interview data shows how they perceived their epistemic agency in their participation in the ESM-based GenEvo curriculum as they learned about complex emergent phenomena and science practices to investigate those phenomena. The analysis of student participation data shows how their epistemically agentic participation entailed shaping knowledge building practices and learning about gene regulation and evolution, and how the ESM-based learning environment supported that. This analysis of restructuration properties instantiated in the ESM design presents the possibilities of supporting students' epistemically agentive learning of emergent phenomena in a biology classroom.

The design features of the GenEvo curriculum provided students with opportunities to participate in building knowledge about emergent biological phenomena related to gene regulation and evolution by shaping in science practices to build knowledge. Students decided which specific aspects of a phenomenon under investigation they wanted to study and how to collect evidence to support their claims. They made observations, formulated research questions, made predictions, designed and conducted experiments, and synthesised information from multiple sources, such as empirical investigations and graphs to construct explanations. They took on the roles of scientific community members, questioned evidence provided by other students, and held each other accountable for providing reliable evidence.

Students typically see teachers as epistemic and content authority in a classroom. To position students with epistemic agency in a classroom teachers need to relinquish some authority to students including epistemic responsibilities (E. Miller et al., 2018). However, positioning students with epistemic agency is not sufficient for their learning of disciplinary content and science practices. To foster students' epistemically agentive learning the learning environment needs to support students in formulating, investigating, and evaluating knowledge claims without seeing the teacher as an ultimate content and epistemic authority in the classroom. The GenEvo ESM served the purpose of being a system that students could use to investigate and evaluate their claims.

The cognitive and social properties of the agent-based restructuration in the GenEvo ESM made it easy to collectively investigate the systems biology phenomena and affective properties made the process enjoyable. The cognitive properties of agent-based restructuration reduced perceptual limitations by providing visual access to agent behaviours and emergent patterns (Goldstone and Wilensky, 2008) whereas social properties made it easy to share ideas to collectively construct knowledge. The restructuration properties not only made the content knowledge accessible to students but also made it easy for students to enact and shape science practices in ways that were sensible to them. These practices ranged from data practices to collect and analyse evidence, naming practices to refer to biological objects, and micro–macro level reasoning practices to make sense of a complex emergent phenomenon.

In the Genetic Switch model of the GenEvo ESM, the behaviour of agents (proteins) was stochastic, which caused variability in results under the same experimental conditions. This feature was designed for students to learn about data variability in experimental systems and the robustness of certain observed patterns despite the underlying variability. Because of this design feature, the classroom community, including the teacher and the students, realised that they needed to conduct multiple experimental trials to establish an observed pattern.

In this ESM-based class, the representational features of computational agents helped students to develop shared vocabulary such as potato-shaped-things and pink triangles to talk about proteins and their functions. Developing shared vocabulary is an important aspect of science practice. Naming conventions of organisms such as SARS-CoV-2, allows scientists across the world to easily share their findings. Sometimes, scientists also use unusual or funny names for naming a species, a star, or a gene. For example, there are Drosophila genes named Swiss Cheese, Cheap Date, or Boss gene (bride of sevenless – because of its connection with another gene called sevenless), or INDY (I'm Not Dead Yet).[1] The shared vocabulary was helpful for students to easily reference the agents to discuss their properties, interactions, and mechanistic involvements in a phenomenon under investigation. In a high school classroom in general, in a science classroom in particular, and in a biology classroom most specifically, vocabulary often hinders student participation and learning. In the ESM-based classroom, students' use of colloquial words supported their collective investigations and sense-making of the modelled phenomena related to genetic regulation and evolution. They could seamlessly transition to more popularly accepted vocabulary as they investigated the functions and uncovered how genetic regulation worked in this system.

In an ESM, agent-level behaviours and interactions are designed to be manipulable, whereas emergent patterns are not directly manipulable. This requires users to make agent-level manipulations to create new or desirable system-level patterns. In the

GenEvo ESM, students observed and manipulated agent-level behaviours and interactions and investigated corresponding changes at the aggregate-level, which allowed them to learn about and shape practices to study the modelled emergent phenomena. For example, Vidya used Samir's observation interactions between DNA and proteins to reason about the regulation of protein production at the cellular level. Vidya also used this knowledge claim to argue for system-level (cell) evolutionary implications for regulation protein production because *they eat up some energy*, and how that is *costly for a cell*.

In addition to cognitive and social properties, the GenEvo ESM exhibited affective properties as well. Restructureated GenEvo microworld made learning of complex ideas in modern biology playful and enjoyable for students. Thus, the cognitive, social, and affective properties of the GenEvo ESM supported students in shaping practices that are important for *doing systems biology* and learning about the modelled emergent phenomena. Using the agent-based models, students could easily ask and investigate what-if questions about an emergent phenomenon and investigate those by changing agent behaviours, and observing the effects on the system (Wilensky & Reisman, 2006). Since these models were designed to be constructionist microworlds, students could easily manipulate the agents to find answers to their questions and study patterns at the system-level. The computational models designed as ESMs served as effective experimental systems to provide students with opportunities to build knowledge of emergent biological phenomena in epistemically agentive ways.

We also want to acknowledge the limitations of this work. Based on the analysis presented in the paper, we cannot make any claims about the prevalence of the effect, nor can we claim that we have identified all the knowledge building practices that can be supported using the ESM-based curriculum. The vignettes that we have presented in this paper are intended to provide illustrative examples of how and what students learned and showcase the potential of the ESM and ESM-based curriculum to support students' epistemically agentive learning.

This work has implications for designing learning environments that aim to support epistemically agentive learning. ESMs which are essentially agent-based computational models of emergent systems designed as constructionist microworlds can serve to provide quick cognitive access for students to exercise their epistemic agency and share their findings to collectively learn about modelled emergent phenomena with elements of enjoyment and playfulness. ESMs can enable pedagogical practices that relinquish epistemic and content authority to students to be in a position to construct and validate their claims about systems that they investigate and learn about.

Ethics statement

This study met the ethics requirements for human subjects research. The study did not involve any procedures that would pose risks or cause harm to the participants. Study procedures were explained verbally and in writing to the participating children and their parents. We obtained written consents from parents and assents from the children. We collected data in the form of pre- and post- tests, student interviews, artifacts, and video recording of student participation in the course. We used data of only consented students in our analysis. The research protocol for the study was approved by Institutional Review Board of Northwestern University (approval number STU00204756).

Note

1. https://www.lubio.ch/fruitfly-gene-names
   These names are based on the physical or behavioural characteristics of mutants of these genes. Brains of fruitflies with a mutation in the Swiss Cheese gene look like swiss cheese. Fruitflies with a mutation in the gene Cheap Date are very susceptible to alcohol.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Abd-El-Khalick, F., BouJaoude, S., Duschl, R., Lederman, N. G., Mamlok-Naaman, R., Hofstein, A., Niaz, M., Treagust, D., & Tuan, H.-l. (2004). Inquiry in science education: International perspectives. *Science Education*, *88*(3), 397–419. https://doi.org/10.1002/sce.10118

Arastoopour, G., Dabholkar, S., Bain, C., Woods, P., Hall, K., Swanson, H., Horn, M., & Wilensky, U. (2020). Modeling and measuring high school students' computational thinking practices in science. *Journal of Science Education and Technology*, *29*(1), 137–161. https://doi.org/10.1007/s10956-020-09811-1

Aslan, U., Dabholkar, S., & Wilensky, U. (2018). Developing multi-agent-based thought experiments: A case study on the evolution of gamete dimorphism. In G. Dimuro & L. Antunes (Eds.), *Multi-Agent Based Simulation XVIII. MABS 2017. Lecture Notes in Computer Science* (Vol. 10798). Cham: Springer. https://doi.org/10.1007/978-3-319-91587-6_4

Berland, L. K., & Lee, V. R. (2012). In pursuit of consensus: Disagreement and legitimization during small-group argumentation. *International Journal of Science Education*, *34*(12), 1857–1882. https://doi.org/10.1080/09500693.2011.645086

Blikstein, P., & Wilensky, U. (2005). Less is more: Agent-based simulation as a powerful learning tool in materials science. *IV International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2005)*. http://ccl.sesp.northwestern.edu/2005/2005-blikstein-wilensky.pdf

Brady, C., Holbert, N., Soylu, F., Novak, M., & Wilensky, U. (2015). Sandboxes for model-based inquiry. *Journal of Science Education and Technology*, *24*(2-3), 265–286. https://doi.org/10.1007/s10956-014-9506-8

Dabholkar, S., Anton, G., & Wilensky, U. (2018). GenEvo - An emergent systems microworld for model-based scientific inquiry in the context of genetics and evolution. In J. Kay & R. Luckin (Eds.), *Rethinking Learning in the Digital Age: Making the Learning Sciences Count, 13th International Conference of the Learning Sciences (ICLS) 2018* (Vol. 3). London: International Society of the Learning Sciences.

Dabholkar, S., Bain, C., & Wilensky, U. (2020). *NetLogo GenEvo 1 Genetic Switch model*. Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University. http://ccl.northwestern.edu/netlogo/models/GenEvo1GeneticSwitch

Dabholkar, S., & Wilensky, U. (2016). *GenEvo Systems Biology Curriculum. Center for Connected Learning and Computer- Based Modeling, Northwestern University*. http://ccl.northwestern.edu/curriculum/genevo/

Danish, J. A. (2013). Designing for technology enhanced activity to support learning. *The Journal of Emerging Learning Design*, *1*(1), 2–7. https://www.learntechlib.org/p/172810

Dey, S., Dabholkar, S., & Joshi, A. (2006). The effect of migration on metapopulation stability is qualitatively unaffected by demographic and spatial heterogeneity. *Journal of Theoretical Biology*, *238*(1), 78–84. https://doi.org/10.1016/j.jtbi.2005.05.013

Duncan, R. G. (2007). The role of domain-specific knowledge in generative reasoning about complicated multileveled phenomena. *Cognition and Instruction*, *25*(4), 271–336. https://doi.org/10.1080/07370000701632355

Duschl, R. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Education*, *32*(1), 268–291. https://doi.org/10.3102/0091732X07309371

Edwards, L. D. (1995). Microworlds as representations. In A. A. DiSessa, C. Hoyles, R. Noss, & L. D. Edwards (Eds.), *Computers and exploratory learning* (pp. 127–154). Springer. https://doi.org/10.1007/978-3-642-57799-4_8

Edwards, L. D. (1997). Exploring the territory before proof: Student's generalizations in a computer microworld for transformation geometry. *International Journal of Computers for Mathematical Learning*, *2*(3), 187–215. https://doi.org/10.1023/A:1009711521492

Erickson, F. (1986). Qualitative methods in research on teaching. In M. Wittrock (Ed.), *Handbook of research on teaching* (pp. 119–161). Macmillan.

Erickson, F. (2010). Classroom ethnography. In P. Peterson, E. Baker, & B. McGaw (Eds.), *International encyclopedia of education* (pp. 320–325). Elsevier.

Gkiolmas, A., Karamanos, K., Chalkidis, A., Skordoulis, C., Papaconstantinou, M., & Stavrou, D. (2013). Using simulations of netlogo as a tool for introducing Greek high-school students to eco-systemic thinking. *Advances in Systems Science and Applications*, *13*(3), 276–298.

Glaser, B. G., & Strauss, A. L. (2017). *The discovery of grounded theory*. Routledge. https://doi.org/10.4324/9780203793206

Goldstone, R. L., & Wilensky, U. (2008). Promoting transfer by grounding complex systems principles. *Journal of the Learning Sciences*, *17*(4), 465–516. https://doi.org/10.1080/10508400802394898

Hmelo-Silver, C. E., & Azevedo, R. (2006). Understanding complex systems: Some core challenges. *Journal of the Learning Sciences*, *15*(1), 53–61. https://doi.org/10.1207/s15327809jls1501_7

Hoyles, C., & Noss, R. (1987). Synthesizing mathematical conceptions and their formalization through the construction of a logo-based school mathematics curriculum. *International Journal of Mathematical Education in Science and Technology*, *18*(4), 581–595. https://doi.org/10.1080/0020739870180411

Keifert, D., Krist, C., Scipio, D. A., & Phillips, A. M. (2018). *Epistemic agency as a members' experience*. International Society of the Learning Sciences, Inc. [ISLS].

Kitano, H. (2002). Computational systems biology. *Nature*, *420*(6912), 206–210. https://doi.org/10.1038/nature01254

Kitano, H. (2017). Biological complexity and the need for computational approaches. In S. Green (Ed.), *Philosophy of systems biology* (pp. 169–180). Springer. https://doi.org/10.1007/978-3-319-47000-9_16

Klopfer, E., Yoon, S., & Perry, J. (2005). Using palm technology in participatory simulations of complex systems: A new take on ubiquitous and accessible mobile computing. *Journal of Science Education and Technology*, *14*(3), 285–297. https://doi.org/10.1007/s10956-005-7194-0

Ko, M. M., & Krist, C. (2019). Opening up curricula to redistribute epistemic agency: A framework for supporting science teaching. *Science Education*, *103*(4), 979–1010.

Krist, C., Machaka, N., Voss, D., Mathayas, N., Kelly, S., & Shim, S.-Y. (2023). Teacher noticing for supporting students' epistemic agency in science sensemaking discussions. *Journal of Science Teacher Education*, *34*(8), 799–819.

Langbeheim, E., & Levy, S. T. (2018). Feeling the forces within materials: Bringing inter-molecular bonding to the fore using embodied modelling. *International Journal of Science Education*, *40*(13), 1567–1586. https://doi.org/10.1080/09500693.2018.1487092

Levy, S. T., & Wilensky, U. (2009). Students' learning with the connected chemistry (CC1) curriculum: Navigating the complexities of the particulate world. *Journal of Science Education and Technology*, *18*(3), 243–254. https://doi.org/10.1007/s10956-009-9145-7

Miller, E., Manz, E., Russ, R., Stroupe, D., & Berland, L. (2018). Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards. *Journal of Research in Science Teaching*, *55*(7), 1053–1075. https://doi.org/10.1002/tea.21459

Miller, K., & Levin, J. (2010). *Biology (Teacher's edition)*. Pearson Prentice Hall.

Müller-Hill, B. (1996). *The Lac Operon: A short history a genetic paradigm*. Walter de Gruyter.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. The National Academies Press.
Noss, R., & Hoyles, C. (2017). Constructionism and microworlds. In E. Duval, M. Sharples, & R. Sutherland (Eds.), *Technology enhanced learning* (pp. 29–35). Cham: Springer. https://doi.org/10.1007/978-3-319-02600-8_3
Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas and powerful ideas*. Basic Books. https://dl.acm.org/citation.cfm?id=1095592
Papert, S., & Harel, I. (1991). Situating constructionism. *Constructionism*, *36*(2), 1–11.
Roschelle, J. M. (1991). *Students' construction of qualitative physics knowledge: Learning about velocity and acceleration in a computer microworld*. University of California.
Russ, R. S., & Berland, L. K. (2019). Invented science: A framework for discussing a persistent problem of practice. *Journal of the Learning Sciences*, *28*(3), 279–301. https://doi.org/10.1080/10508406.2018.1517354
Scardamalia, M., & Bereiter, C. (1991). Higher levels of agency for children in knowledge building: A challenge for the design of new knowledge media. *The Journal of the Learning Sciences*, *1*(1), 37–68. https://doi.org/10.1207/s15327809jls0101_3
Schwarz, C. V., Passmore, C. M., & Reiser, B. J. (2017). Moving beyond "knowing about" science to making sense of the world. In C. V. Schwarz, C. M. Passmore, & B. J. Reiser (Eds.), *Helping students make sense of the world through next generation science and engineering practices* (pp. 3–21). NSTA Press.
Sengupta, P., & Wilensky, U. (2009). Learning electricity with NIELS: Thinking with electrons and thinking in levels. *International Journal of Computers for Mathematical Learning*, *14*(1). https://doi.org/10.1007/s10758-009-9144-z
Small, M. L. (2011). How to conduct a mixed methods study: Recent trends in a rapidly growing literature. *Annual Review of Sociology*, *37*(1), 57–86. https://doi.org/10.1146/annurev.soc.012809.102657
Stieff, M., & Wilensky, U. (2003). Connected chemistry—incorporating interactive simulations into the chemistry classroom. *Journal of Science Education and Technology*, *12*(3), 285–302. https://doi.org/10.1023/A:1025085023936
Striedter, G. (2022). *Model systems in biology: History, philosophy, and practical concerns*. MIT Press.
Stroupe, D. (2014). Examining classroom science practice communities: How teachers and students negotiate epistemic agency and learn science-as-practice. *Science Education*, *98*(3), 487–516. https://doi.org/10.1002/sce.21112
Svihla, V., & Linn, M. C. (2012). A design-based approach to fostering understanding of global climate change. *International Journal of Science Education*, *34*(5), 651–676. https://doi.org/10.1080/09500693.2011.597453
Turkle, S. (2007). Introduction: The things that matter. In S. Turkle (Ed.), *Evocative objects: Things we think with* (pp. 3–10). The MIT Press. http://www.jstor.org/stable/j.ctt5hhg8p.4
Vitale, J. M., McBride, E., & Linn, M. C. (2016). Distinguishing complex ideas about climate change: Knowledge integration vs. specific guidance. *International Journal of Science Education*, *38*(9), 1548–1569. https://doi.org/10.1080/09500693.2016.1198969
Wagh, A., Cook, Whitt, K., & Wilensky, U. (2017). Bridging inquiry-based science and constructionism: Exploring the alignment between students tinkering with code of computational models and goals of inquiry. *Journal of Research in Science Teaching*, *54*(5), 615–641. https://doi.org/10.1002/tea.v54.5
Wagh, A., & Wilensky, U. (2018). EvoBuild: A Quickstart toolkit for programming agent-based models of evolutionary processes. *Journal of Science Education and Technology*, *27*(2), 131–146. https://doi.org/10.1007/s10956-017-9713-1
Wilensky, U. (1999). *NetLogo. Center for Connected Learning and Computer-Based Modeling, Northwestern University*. http://ccl.northwestern.edu/netlogo/.
Wilensky, U. (2001). Modeling nature's emergent patterns with multi-agent languages. *Proceedings of EuroLogo*.

Wilensky, U. (2003). Statistical mechanics for secondary school: The GasLab multi-agent modeling toolkit. *International Journal of Computers for Mathematical Learning*, *8*(1), 1–41. https://doi.org/10.1023/A:1025651502936

Wilensky, U. (2020). Restructuration theory and agent-based modeling: Reformulating knowledge domains through computational representations. In N. Holbert, M. Berland, & Y. B. Kafai (Eds.), *Designing Constructionist Futures: The Art, Theory, and Practice of Learning Designs* (pp. 287–300). MIT Press.

Wilensky, U., & Novak, M. (2010). Teaching and learning evolution as an emergent process: The BEAGLE project. In Taylor, R. & Ferrari, M. (Eds.), *Epistemology and science education: Understanding the evolution vs. intelligent design controversy*, 213–243. New York: Routledge.

Wilensky, U., & Papert, S. (2010). Restructurations: Reformulations of knowledge disciplines through new representational forms. *Constructionism*.

Wilensky, U., & Rand, W. (2015). *An introduction to agent-based modeling: Modeling natural, social, and engineered complex systems with NetLogo*. MIT Press.

Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, a sheep, or a firefly: Learning biology through constructing and testing computational theories - An embodied modeling approach. In *Cognition and Instruction* (Vol. 24, Issue 2). https://doi.org/10.1207/s1532690xci2402_1

Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems approach to making sense of the world. *Journal of Science Education and Technology*, *8*(1), 3–19.

Wilkerson-Jerde, M., Wagh, A., & Wilensky, U. (2015). Balancing curricular and pedagogical needs in computational construction kits: Lessons from the DeltaTick project. *Science Education*, *99*(3), 465–499. https://doi.org/10.1002/sce.21157