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Computational participation and the learner-technology pairing in K-12 STEM education

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Abstract
The role of technology in STEM education remains unclear and needs stronger operational definition. In this paper, we explore the theoretical connection between STEM and emergent technologies, with a focus on learner behaviors and the potential of technology-mediated experiences with computational participation (CP) in shaping STEM learning. In particular, by de-emphasizing what technology is used and bringing renewed focus to how the technology is used, we make a case for CP as an epistemological and pedagogical approach that promotes collaborative STEM practices. Utilizing Ihde's work as a conceptual framework, we explore how technology-mediated relations shape STEM learner experiences and behaviors by empowering learners to develop scientific knowledge through collaborative participation and interactive relationships with technology. In particular, we focus on technology mediated game-based learning and citizen science, and examine how CP creates opportunities for STEM learners to leverage learning with technology in innovative ways. We argue that through computational and collaborative learning experiences, learners participate as members of STEM learning communities in ways that mirror how STEM professionals collaborate, applying interdisciplinary and transdisciplinary approaches to complex real-world problems. Computational participation consequently creates opportunities for learner-technology pairings to (re)shape STEM learning behaviors, empowering learners to engage collaboratively as members of a STEM community of practice.

KEYWORDS
collaborative learning, computational participation, computational thinking, community of practice, citizen science, game-based learning, learner-technology, STEM practices, STEM education, technology

Advances in computing and information technologies over the past four decades have resulted in innovative applications of computational technologies across multiple disciplines (Swaid, 2015). This paper is grounded in a conceptualization of science, technology, engineering, and mathematics (STEM) that embraces the advent of modern technologies and calls for emergent technologies to continually redefine the T in STEM education. We examine how computational participation integrates emergent technologies as both tools and practices, and serves as an epistemological and pedagogical approach that promotes collaborative STEM practices.

In the context of STEM practices, the term *emerging* or *emergent technologies* has in recent decades included a variety of innovations related to information and communication technologies, biotechnology, and nanotechnology (Einsiedel, 2009). Emergent technologies, consequently, are defined to encompass a wide variety of devices, tools, artifacts, and representations that continually shape the landscape of scientific investigations, knowledge advancement, and practices, by enabling increased access to the world around us. In a literature review of emergent technologies in the field of science education, Oliveira et al. (2019) argued that emergent technologies (including computational thinking, simulations and virtual labs, pedagogic robotics, mobile devices, computational modeling, gaming and technology-mediated play, and artistic technologies) shape how K-12 learners indirectly relate to the physical world through technological representations and technology-mediated interactions. Oliveira and colleagues used the term emergent technologies broadly, including emergent technology tools and devices (simulations and virtual labs, pedagogic robotics, mobile devices, gaming and technology-mediated play, creative and artistic technologies) and emergent technology practices (computational modeling and computational thinking). In this paper, we examine how the use of computational participation as an epistemological and pedagogical approach in STEM education creates opportunities for K-12 STEM learners to utilize technological practices used by STEM professionals, allowing learners to engage in authentic STEM practices. We look at how technological approaches, such as technology-mediated game-based learning and citizen science projects, mediate STEM learner experiences and behaviors by empowering learners to develop scientific knowledge through collaborative participation and interactive relationships with technology. In addition, we examine how computational participation creates opportunities for learner-technology pairings that (re)shape STEM learning behaviors, and empowers learners to engage as members of a STEM community of practice.

1 | INTEGRATED STEM AND THE T IN STEM EDUCATION

Current policy documents call for K-12 science classrooms to employ integrated STEM strategies to provide a more authentic learning environment for learners. For example, the addition of engineering in the science education standards (NGSS Lead States, 2013) acknowledges not only that learners need to engage in learning about natural phenomena in science, but also that teaching and learning should address the human-constructed and technological world in which we live. Unfortunately, there is a lack of consensus on a definition of integrated STEM (e.g., Breiner, Harkness, Johnson, & Koehler, 2012; Brown, Brown, Reardon, & Merrill, 2011; Bybee, 2010; English, 2016; Koehler, Binns, & Bloom, 2016; Ring, Dare, Crotty, & Roehrig, 2017; Sgro, Bobowski, & Oliveira, in press). However, there is some agreement on desired learner behaviors related to engagement with integrated STEM. Integrated STEM instruction should engage learners in solving real-world problems that require learners to apply scientific, mathematical, and engineering concepts to authentic problems (Breiner et al., 2012; Brown et al., 2011; Kelley & Knowles, 2016; Kennedy & Odell, 2014; Moore et al., 2014; Sanders, 2009). Learners are expected to participate in design thinking, applying the practices of science and engineering to propose explanations and design solutions (NRC, 2012). It is expected that learners should develop teamwork, communication, critical thinking, and other 21st century competencies by engaging in integrated STEM activities (Brown et al., 2011; Honey, Pearson, & Schweingruber, 2014; Kennedy & Odell, 2014; Moore et al., 2014). While some of the desired learner behaviors are agreed upon, the lack of clear and consistent conceptualizations of STEM makes it difficult to achieve these goals.

Although there is consensus on certain aspects of STEM integration, the role of technology in STEM education remains particularly unclear and needs stronger operational definition (Honey et al., 2014; Sivaraj, Ellis, & Roehrig, 2019). Ellis et al. (2020) reviewed several common perspectives on the T in STEM education, which included technology as (a) the product of engineering, (b) instructional technologies, (c) computational thinking, and (d) tools and practices used by science, mathematics, and engineering professionals. In this paper, we seek to expand the theoretical perspective of the T in STEM, with a focus on learner behaviors and the potential of technology-mediated experiences with computational participation in shaping STEM learning. In particular, we wish to de-emphasize the *what* about technology (i.e., a focus on specific products, tools, and software) and bring renewed focus to the *how* associated with these technologies (i.e., the behaviors, practices, and outcomes that impact student learning).

We define STEM practices based on the science and engineering practices identified by the *Framework for K-12 Science Education* (NRC, 2012), a national policy document that seeks to address challenges related to how scientific concepts are often taught disconnected from scientific practices. These practices include: asking questions (for science) and defining problems (for engineering); developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics and computational thinking; constructing explanations (for science) and designing solutions (for engineering); engaging in argument from evidence; and obtaining, evaluating, and communicating information. Because these STEM practices are consistent with the type of work done by science, engineering, and mathematics professionals, students' use of STEM practices engages them in more authentic learning experiences. Below, we discuss computational thinking, a relatively recent approach to using technology in K-12 classrooms that engages students in these kinds of learning experiences.

2 | COMPUTATIONAL THINKING IN STEM EDUCATION

From the introduction of Logo as a programming language in the 1980s to programmable LEGO Bricks in the mid-1990s and more recent innovations in programmable interfaces, there continues to be a surge in the incorporation of computational activities in STEM learning experiences. The remarkable growth in computational opportunities offered across K-12 STEM learning in particular has led to the creation of tangible products as well as computer programs that control these products (e.g., Blikstein & Wilensky, 2009; Kynigos, 2007).

Papert (1980) used the term *computational thinking* (CT) to describe how computational representations and programming enabled learners to make their thinking more apparent by constructing, deconstructing, and reconstructing artifacts. More recently, Wing (2006) defined CT to include diverse aspects of designing systems, solving problems, and understanding human behavior. Similarly, Barr and Stephenson (2011) presented CT as a problem-solving process, which includes decomposing a problem in order to make it solvable using computational tools, analyzing and representing data systematically, utilizing algorithms, and applying a wide range of solutions.

Researchers have noted the overlap of these CT practices (such as problem representation, abstraction, decomposition, simulation, verification, and prediction) with scientific and mathematical practices, making a case for integrating CT into K-12 STEM curricula (Sengupta, Kinnebrew, Basu, Biswas, & Clark, 2013). Several scholars support the view that CT is highly compatible with STEM instruction and can be an effective practice in STEM classrooms, which are also focused on problem solving (e.g., Ellis et al., 2020; Kynigos, 2007; Weintrop et al., 2016; Wilensky & Reisman, 2006). Thus, it is unsurprising that the *Framework for K-12 Science Education* (NRC, 2012) included CT as one of the essential science and engineering practices that K-12 students should engage in. Built from the *Framework*, the Next Generation Science Standards (NGSS) specifically describes CT as "strategies for organizing and searching data, creating sequences of steps called algorithms, and using and developing new simulations of natural and designed systems" (NGSS Lead States, 2013, Appendix F, p. 10). Learners are, therefore, expected to deepen their understanding of core concepts using CT and engaging with scientific and engineering practices as outlined in the NGSS.

In science classrooms, technology tools and devices are primarily focused on practices related to data collection. For instance, virtual laboratories or simulations are used as a replacement for collecting data in a physical space. Similarly, sensors on mobile devices are increasingly utilized to gather data efficiently. In essence, these are examples of technology as a tool to help learners engage in the same scientific practices used by scientists as a replacement (virtual vs. physical laboratory), as a way to improve efficiency (sensors vs. traditional tools), or as affordances to collect data that would otherwise be unavailable (slow motion cameras, simulations, computer models). While emergent technological tools can and should be used to reduce burdens on materials, time, and cognitive load, we seek to advance the argument that the use of technologies in STEM education must move beyond tool-based approaches focused on data collection.

3 | COMPUTATIONAL PARTICIPATION IN STEM EDUCATION

Kafai and Burke (2014) extended the discussion of CT in educational contexts, calling for CT to be reframed as *computational participation* (CP), emphasizing "the ability to solve problems with others, design systems for and with others, and draw on computer science concepts, practices, and perspectives (p. 6)" so that learners are able to meaningfully participate as critical thinkers, as well as producers, consumers, and distributors of technology. They argue that CP enables insight into sociological and cultural dimensions as learners move between the digital and physical world. CP, therefore, includes not just CT skills, but also utilizes CT skills toward specifically purposed, collaborative projects, such as using code to generate websites, programming to create interactive art projects and digital stories, and interacting through computational activities to build and sustain relationships. Utilizing this perspective, we make a case for using CP to unpack the potential of the T in STEM, which can create authentic and collaborative opportunities for STEM learners to engage in STEM practices through interactions with technologies.

3.1 | Computational participation as an epistemological and pedagogical approach

We propose that CP has the potential to integrate continually evolving technological tools, providing opportunities for STEM learners to move between digital and physical worlds, constructing knowledge of concepts and skills through collaborative STEM-related practices and collaborative interactions with emergent technologies. We share examples of specific approaches (such as technology-mediated gaming and citizen science) in STEM learning that reveal the power of CP as an epistemological and pedagogical approach to integrating a wide range of technologies that promote STEM practices and learner behaviors. We argue that, through computational and collaborative components in learning experiences, learners participate as members of STEM learning communities in ways that mirror how STEM professionals collaborate, applying interdisciplinary and transdisciplinary approaches to complex real-world problems. Within STEM education, CP requires the collaborative application of CT and STEM practices, as learners interact with technologies and with each other as members of a learning community. Learners' interactions with technologies and others allow them to engage simultaneously in social and discipline-specific practices as members of a STEM community of practice, taking on critical roles as makers, designers, and innovators.

4 | THEORETICAL FRAMEWORK

The theoretical framework for this paper is grounded in communities of practice (Wenger, 1998), where learning is necessarily relational, situated, and dependent on interactions with the learning environment. Specifically, a community of practice (CoP) is a group of people with common goals, who come together by engaging in shared ways of doing things (practices) and committing to a shared domain of interest (Lave & Wenger, 1991; Wenger, 1998). Wenger (1998) describes three defining characteristics for a CoP as (a) shared domain of interest, (b) shared community built through interactions, and (c) shared repertoire of resources and practices. Members of a CoP develop a

TABLE 1 Technology-mediated relations for the STEM learner (based on Ihde, 1991)

T-mediated relations	Learner relating to world	STEM example
Embodiment	Observes the world, T becomes transparent	Telescopes, electron microscopes
Hermeneutic	Interprets the world, reading T	Thermometers, pH sensors
Alterity	Focus on technology, world becomes secondary	Robots, citizen science apps
Background	Implicitly accepts T as part of the context/ physical world	Air conditioners, projectors

shared system of values and practices, which new members gradually learn and take on as they engage in interactions.

In our work, the learning environment includes individuals (both peers and mentors), technology, information, and artifacts. Learning, constructing meaning, and developing transferable knowledge of concepts and practices are viewed as relational processes, shaped by interactions embedded in cultural, historical, and social contexts, where knowledge and behavior are constructed through shared repertoires of discourse, interactions, and practices (Wenger, 1998); these include learners' interactions with each other and with various material, social, and cultural components in their learning environment (John-Steiner & Mahn, 1996). The learner is significant not as a receiver of knowledge, but in terms of what they bring to the digital and physical learning environment as an active (and interactive) problem-solver. Behavior and learning, therefore, significantly and dynamically evolve through social, collaborative interactions.

With a focus on CP in STEM education and learners as members of STEM CoPs, this theoretical framework allows us to explore how the learner-technology pairing shapes learner behaviors and their use of STEM practices. As STEM learners interact with emergent technologies, using a CoP theoretical lens guides us toward examining the social and collaborative aspects of these interactions and the learning opportunities that such interactions afford. In this paper, we examine how learners access authentic STEM learning experiences as members of a STEM CoP and how CP creates opportunities for STEM learner-technology pairings to shape learner behaviors through collaborative interactions with emergent technologies.

5 | CONCEPTUAL FRAMEWORK

To better understand how the learner-technology pairing shapes student behaviors in STEM educational settings, we utilize Ihde's philosophical work as a conceptual framework. Ihde (1991) argued that technology is inherent in the pursuit of scientific knowledge because the human-technology pairing shapes how scientists construct meaning. This pairing is experiential, influencing how both scientists and learners relate to the world, as well as collaborative and embedded within a social context in which the human-technology pairing continually shapes how learning and society evolve (Ihde, 1993). In this perspective, technology is not merely an aid for learning; rather, technology is an essential mediator that shapes scientific investigation and discovery through the human-technology pairing. In particular, irrespective of whether technology is understood as devices, tools, representations, or artifacts, technology and science are symbiotically interconnected because technology-mediated relations shape the epistemic evolution of scientific knowledge and practices (Ihde, 1991).

Ihde (1991) described four types of technology-mediated relations: *embodiment*, *hermeneutic*, *alterity*, and *background* relations. Table 1 summarizes these four relations and provides examples of technologies that mediate these relations in STEM contexts. In their review of emergent technologies in the field of science education, Oliveira et al. (2019) found that the field "has become increasingly characterized by hermeneutic and alterity relations wherein the physical world is experienced indirectly through technological representations…" (p. 156). Thus, utilizing Ihde's work as a conceptual framework, we focus on technology-mediated hermeneutic and alterity relations within the context of CP as STEM learners interact with technologies. We discuss how these relations shape STEM learning behaviors.

In *hermeneutic* relations, technology shifts the learner's perceptions by making the physical world more accessible by offering numeric or coded data, which allows for inferential and logical analysis of the world beyond what our senses can perceive. For example, the learner must interpret the display on a thermometer, which provides output in the form of temperature readings that allow us to quantify heat. Other examples include pH and gas pressure sensors, which provide insight as the learner reads, interprets, and reflects on numerical readings that represent what cannot be quantified by our senses. Consequently, hermeneutic relations allow learners to read data captured by technology and to subsequently interpret output provided by technology as a representation of the physical world.

In *alterity* relations, learners engage with technology as an independent, anthropomorphic entity, and generally as a focal point that causes the physical world to become secondary (Ihde, 1991). Navigational tools like Google Maps and SatNav, for example, are often viewed as intelligent machines, performing actions by responding to symbols, text, or voice commands, and even capable of eliciting emotional responses, trust, and attachment from humans during interactions (Brey, 2000; Hogan & Hornecker, 2011). Interactions with intelligent robots, simulations, and digital games are examples of alterity relations in classrooms, where the technology is often viewed as quasi-autonomous and mediates how learners reflect on the physical world as they interact with and respond to technologies.

TABLE 2 Clarifying digital game-based learning platforms

Digital game-based learning	Primarily understood as…	STEM example
Educational simulations	2-D; instructional and interactive, but not necessarily immersive	Virtual labs
Serious educational games	3-D immersive environment; pedagogical approach embedded into storyline; (STEM) content explicitly integrated into gameplay	Investigating through gaming to solve STEM-related problems (e.g., why fish in an ecosystem are dying)
Augmented reality	3-D haptic learning; superimposes digital image to integrate virtual environment into existing physical world; generally, utilizes simulations with mobile/handheld devices	Simulations to perform mock surgeries

In the sections that follow, we reflect on how CP leverages technology-mediated hermeneutic and alterity relations, creating meaningful opportunities for collaborative interactions between learners and technologies through STEM practices. We also examine technological intentionality within the context of CP, and how the learner-technology pairing shapes learner behavior with respect to STEM practices by drawing on empirical examples to make a case for the potential of CP within STEM learning contexts. For example, when learners use simulations to examine specific phenomena, the STEM context creates the intentional circumstances for interactions with technologies in use to facilitate learning. STEM learners, consequently, have opportunities to leverage technology-mediated relations and engage in authentic STEM practices. In particular, we focus on technology-mediated game-based learning and citizen science, which are relatively new approaches in STEM contexts (Bonney et al., 2014; Oliveira et al., 2019), and examine how CP as an epistemological and pedagogical approach can create opportunities for STEM learners to leverage learning with technology in innovative ways.

6 | EXAMPLES OF CP IN STEM EDUCATION

In the following sections, we share two learning experiences from game-based learning and citizen science, and examine these as examples of CP providing computational and collaborative opportunities to STEM learners. We explore technology-mediated relations during these learning experiences for STEM learners. Reflecting on these examples, we draw attention to computational and collaborative components of each learning experience. To identify computational components, we use categories proposed by Weintrop et al. (2016), which include (a) data practices, (b) modeling and simulation practices, (c) problem-solving practices, and (d) systems thinking practices. The presence (or absence) of activities that match these categories demonstrates the extent to which CP integrates both CT skills and STEM practices through collaborative learning experiences. We also examine how CP enables learners to leverage social, collaborative aspects of learning.

6.1 | Game-based learning and STEM education

Although simulation-based games have a long history, it was not until the 1970s that simulation techniques and gaming were used for teaching science and technology (Ellington, Gordon, & Fowlie, 1998). Educational simulations are a basic form of digital games that are generally understood as interactive, instructional, 2-dimensional environments that create a conceivable reality, where learners can manipulate variables in order to explore different real-life scenarios and systems (Aldrich, 2004). Digital game-based learning has evolved in the last two decades, with electronic and digital games becoming increasingly more accessible to K-12 learners (Echeverría et al., 2011; Shaffer, Squire, Halverson, & Gee, 2005). Digital games include a wide variety of games on a console, handheld device, smartphone, or computer, and also include an array of genres and platforms, such as simulations, serious educational games, and augmented reality games. Table 2 provides a brief summary of different digital game-based learning platforms, with examples of each within a STEM-related context.

Lamb, Annetta, Firestone, and Etopio (2018) noted that developments in the early 2000s (such as improvements in processing power, graphical rendering, and memory formats) enabled the gaming industry to create realistic settings with interactive capabilities. These developments led to the advent of *serious educational games* (SEGs), video games designed with an intentional, specific pedagogical approach (Annetta & Shymanski, 2006). Lamb et al. (2018) also compared outcomes related to different digital gaming platforms, noting that a game-based approach to learning promotes improved learner attitudes, cognition, and behaviors, including motivation, creativity, reasoning skills, and engagement.

Several scholars argue that gaming as a pedagogical approach enhances specific cognitive and social skills related to STEM learning, such as pattern recognition, spatial visualization and reasoning skills, higher order thinking, literacy, creativity, decision-making, and engagement (e.g., Annetta, Cook, & Schultz, 2007; Dondlinger, 2007; Lamb, Annetta, & Vallett, 2015; Wauck, Xiao, Chiu, & Fu, 2017). Researchers also make a case for how digital game-based learning allows learners to change conditions by manipulating variables while thoughtfully considering different outcomes (Sneider, Stephenson, Schafer, & Flick, 2014). Consequently, the learner-technology pairing creates opportunities for learners to confront misconceptions and to develop metacognitive awareness, as learners simultaneously design and redesign algorithms through strategic thinking and critical reasoning, toward creating alternate scenarios or innovative solutions (Scarlatos, Tomkiewicz, & Courtney, 2013). Scholars also emphasize how gaming helps learners with conceptual understanding, along with domain-specific knowledge and practices, especially when learners contribute to game design or creation of new games (Mitchell & Savill-Smith, 2004).

However, there is continued debate, resistance, and skepticism related to the value, use, implementation, and appropriateness of incorporating gaming as instructional technology (Rice, 2007). Researchers, therefore, call for the inclusion of thoughtful pedagogical approaches along with appropriate instructional facilitation to maximize the potential of well-designed games in STEM learning (Barab & Dede, 2007; Echeverría et al., 2011). Effective game design and productive pedagogical approaches that take into consideration theoretical perspectives related to the role of technology in STEM learning, for instance, contribute toward the integration of inquiry-driven multiplayer games in STEM contexts, which foster collaborative learning, along with positive STEM learning behaviors. In the following sections, we explore CP as a thoughtful pedagogical approach to maximizing STEM learning within a gaming experience.

6.2 | Whypox: Experiencing a virtual pandemic

6.2.1 | The STEM gaming experience in Whypox

Whyville (www.whyville.net) was created as an educational virtual world that could serve as an engaging science environment (Kafai, Feldon, Fields, Giang, & Quintero, 2007; Kafai & Fields, 2013; Kafai, Quintero, & Feldon, 2010; Neulight, Kafai, Kao, Foley, & Galas, 2007). The virtual world was designed with a rich, reality-based context, including an economy (where each player received a daily salary), a newspaper, and multiple opportunities for interactive STEM engagement through various science and mathematics tasks/activities. This multi-user virtual environment was integrated into a 10-week science curriculum about infectious disease across two sixth grade classes. Learners accessed the Whyville website in science class and outside school, creating avatars, or online representations. Through these avatars, learners experienced the outbreak of a virtual epidemic called Whypox.

Whypox was a flu-like virus with symptoms that included alterations to avatar appearance (red spots) and communication (sneezes in chats). As avatars interacted with other community members in the virtual world, proximity to symptomatic members resulted in the spread of the virus. As a virtual community of epidemiologists, learners investigated the spread of Whypox, engaging in inquiry-driven STEM learning using infection and epidemic simulators in the Whyville Center for Disease Control (CDC), where they developed understandings related to the spread of infectious disease. In later iterations of the game, learners were also able to visit a virtual BioPlex center in Whyville to create virtual vaccines and variations of the WhyFlu virus. Throughout the gaming experience, STEM learners participated in various classroom activities in the physical world, such as using microscopes to examine cells, completing worksheets related to cells, bacteria, and viruses, building and updating concept maps related to infectious disease, and engaging in teacher-facilitated whole class discussions related to experiences in Whyville.

6.2.2 | CP during the Whypox investigation

As learners entered the virtual world of Whyville, CP provided multiple opportunities for them to engage in STEM practices based on their interest and familiarity with social and discipline-specific components. These opportunities included exploring science and mathematics tasks as teams, conducting collaborative research and writing related to the history of Whypox, and role-playing to take on different STEM-related roles, such as epidemiologists and research scientists. Learners investigated how infectious disease spreads through a population by tracking the movements of avatars before and after they were infected. The documentation of the spread of Whypox took place both online, using asynchronous community bulletin boards, as well as offline in whole class discussions, using wall-sized charts, concept maps, and other organizers in the classroom. Learners also examined the spread of Whypox by visiting Whyville's CDC as teams of scientists, using simulation and graphing tools to analyze data, make predictions, and manipulate variables, using mathematical models and computational thinking to generate different outcomes. The multi-user design and multiple modes of engagement created an authentic, collaborative context. Learners worked as a team using tools, such as simulators, not just as data practices, but to situate their data analysis with systems thinking practices. Web-based tools embedded in this virtual world facilitated efficient data practices, such as data collection and representation, thereby enabling learners to focus collaborative efforts toward data analysis and the creation of explanations and models. Thus, the learner-technology pairing facilitated STEM learners' collaborative development of scientific knowledge, concepts, and practices. Table 3 shows examples of specific STEM practices, along with computational components as learners engaged in the Whypox investigation.

Learners also worked collaboratively toward explanations of the spread of the epidemic as a virtual community of scientists, mirroring practices used by STEM professionals, interacting with technology and each other in digital and physical spaces. For example, learners had opportunities to “visit” the BioPlex center and explore vaccines and virus variants through coding. They were able to determine when and how to distribute these vaccines, considering scientific and ethical issues during collaborative decision making. Thus, the learner-technology pairing supported collaborative STEM practices, such as constructing explanations and developing and using models, while

TABLE 3 Examples of Whypox investigation activities with STEM practices

Whyville STEM activity	STEM practices	Computational components
Identifying source of infection by tracking avatars' movements; discussing trends and hypotheses related to symptoms	Planning and carrying out investigations; analyzing and interpreting data	Problem-solving practices; systems thinking practices
Utilizing infection and epidemic simulators to analyze data and develop alternate models of epidemic and exponential growth	Analyzing and interpreting data; developing and using models; using mathematical and computational thinking	Modeling and simulation practices; systems thinking practices
Designing a vaccine and creating a virus variant in the Bioplex center	Constructing explanations and designing solutions	Problem-solving practices; systems thinking practices

approaching the inquiry from different perspectives (e.g., as a research scientist, data analyst, and vaccine developer). As STEM learners engaged in inquiry, they had authentic opportunities to collaboratively solve complex problems as a virtual community of scientists. Their use of emergent technologies, computational thinking, and collaboration as members of a STEM CoP in both the digital and physical world provide a useful example of CP in practice.

6.2.3 | Technology-mediated relations shape learner behaviors during Whypox investigation

In this gaming experience, technology-mediated relations shaped how the learner-technology pairing empowered STEM learners to evaluate and analyze information related to the virtual epidemic and connect their learning to how infections spread in populations in the physical world. Within the Whypox context, technology-mediated relations included hermeneutic and alterity relations, as learners used various web-based simulators to generate data output that was used to interpret and understand the spread of Whypox. Alterity relations also shaped how learners manipulated variables (e.g., days of incubation) to create alternate scenarios for the epidemic using simulation tools. Through these technology-mediated relations, learners were able to collaboratively obtain and evaluate information to construct explanations and build understandings related to the physical world indirectly, transferring knowledge of concepts and practices between the digital and physical world. Even though learners were not directly studying the physical world, technology-mediated hermeneutic and alterity relations shaped learners' perceptions, interpretations, and understandings of an epidemic in the virtual world, and, by extension, in the physical world. Learners constructed meaning in collaborative experiences offered through CP, mediated by their interactions within the game-based learning environment.

6.3 | Citizen science and STEM education

The creation of public interest groups and engagement of volunteers from the general public to form coalitions with goals related to advancing scientific knowledge and environmental stewardship has a long tradition, with science has been integrally connected with spheres of civics, economics, and politics (Dickinson & Bonney, 2012). For example, journals and other artifacts from the 17th century indicate that amateur naturalists collected specimens, recorded observations, and advanced knowledge related to habitats (Miller-Rushing, Primack, & Bonney, 2012). Similarly, volunteer associations of amateur field naturalists have led organized efforts to integrate ecological education and conservation since the late nineteenth century, shaping the formation of societies like Nature London and Nature Canada. *Citizen science* was a phrase initially introduced by Kerson (1989), who described the Audubon Society's acid rain campaign, where "volunteers collect[ed] rain samples, test[ed] their acidity levels, and report[ed] the results to Audubon headquarters" (p. 11). Subsequently, the reports generated using these results were used to lobby Congress, thus mobilizing participation of citizens from all 50 states in an effort to influence national policies. In the last two decades, public engagement in interdisciplinary and transdisciplinary STEM fields, such as environmental and agricultural sciences, has resulted in citizen science evolving as a distinct research model, with a "growing, global citizen science community devoted to working together to bridge the science-society-policy interface" (Hecker et al., 2018, p. 4).

In recent years, with the evolution of user-friendly websites, easily accessible databases, and a wide range of convenient mobile apps, citizen science projects have found their way into formal and informal STEM learning environments, where learners are involved directly in real-time research as members of a larger learning community (e.g., Higgins et al., 2016; Raddick et al., 2010). Emergent technologies like mobile apps provide platforms for learners to contribute directly to data practices, resulting in large data sets that advance understandings related to the physical world in real time. Table 4 lists five different types of citizen science projects identified by Wiggins and Crowston (2010), with examples of each in a STEM context.

Researchers have made a case for technology-mediated citizen science to be incorporated into K-12 STEM learning in order to foster an action-oriented approach toward STEM learning, use of authentic STEM practices, and an appreciation of civic engagement through STEM (e.g., Meyer et al., 2014; Mueller, Tippins, & Bryan, 2012). For example, Harris and Ballard (2018) discussed how third-graders participated in citizen science through *The Lost Ladybug Project*, utilizing a web-based platform to document local ladybug species through art

TABLE 4 Examples of five types of citizen science projects (based on Wiggins and Crowston, 2010)

Type of project	Primary characteristics	STEM example
Action	Encourages participant intervention in local concerns; co-created or citizen-created; civic engagement	Monitor my watershed: Watershed monitoring utilizing mobile apps to collect and analyze water quality
Conservation	Place-based; contributory or collaborative, with emphasis on stewardship; affiliated with larger state or federal agencies	iNaturalist app: Identifying wildlife or specific species utilizing mobile apps contributing toward creation of extensive field guides
Investigation	Focused on scientific research and data collection; regional to international; contributory, with emphasis on data collection	IveGot1 Bugwood app: Helping scientists track spread of invasive species utilizing apps that document photos or GPS locations
Virtual	Technology-mediated, with no physical world component; contributory, with emphasis on data collection	Planet four, Zooniverse: Contributing to exploration of the surface of Mars by examining images from NASA and sharing observations as input
Education	Explicitly education-oriented; offer learning resources and cumulative learning experiences; contributory and collaborative; affiliated with multiple partner organizations	Journey north: Collecting, sharing, and analyzing evidence about seasonal change by utilizing websites apps to track and share observable changes

and photography. The authors described how learners developed agency when they had opportunities to take ownership of data quality, to share their findings with outside audiences, and to engage with complex, socio-ecological systems, creating a year-round ladybug habitat in collaboration with experts, for instance.

Participation in citizen science projects has been connected to enjoyment, motivation, literacy, cognitive processes, competence, self-efficacy, social community, and experiences in authentic scientific research in real time, including opportunities for direct communication with STEM professionals (e.g., Green & Medina-Jerez, 2012; Phillips, Ferguson, Minarchek, Porticella, & Bonney, 2014; Raddick et al., 2010). However, citizen science projects are often designed primarily as contributory projects with a focus on the collection of high-quality data, limiting interactions with emergent technologies to data practices (Bonney et al., 2009). Several scholars call for co-created projects to be designed to enable learners to participate with more agency, utilizing technologies to collect, analyze, and interpret data, while actively engaging with STEM professionals through various steps of the scientific process (e.g., Ballard, Dixon, & Harris, 2017; Shah & Martinez, 2016). Raddick et al. (2010) discuss how citizen science has the powerful potential to meet the needs of research and education simultaneously. Several scholars emphasize the need for research-based approaches toward meaningfully incorporating citizen science in K-12 STEM curricula, designing projects with ethical considerations of informed consent and participation, and thoughtful consideration of design elements that foster authentic experiences and collaborative learning (Hiller & Kitsantas, 2014; Martin, 2017; Reiheld & Gay, 2019; Sturm et al., 2018). Scholars also point out overlaps between inquiry-driven STEM practices and civic engagement, making a case for citizen science to be incorporated into K-12 STEM curricula and instruction with thoughtful support for teachers through professional development so that technological tools can be used by learners in ways that promote STEM and civic engagement, along with motivation to take on real-world ecological challenges (Condon & Wichowsky, 2018). Below, we examine CP as a pedagogical approach within a technology-mediated citizen science experience incorporated into STEM curricula.

6.4 | WeatherBlur investigations: Co-creating STEM inquiry

6.4.1 | The STEM experience in WeatherBlur investigations

Utilizing a community-based citizen science web-based platform called WeatherBlur (https://mmsa.org/projects/weatherblur/), established by the Maine Math and Science Alliance, learners in elementary and middle schools engaged in investigations related to local issues as part of their science curricula (Kermish-Allen, Peterman, & Bevc, 2019; Plummer & VanDis, 2019). Instead of taking on a predefined investigation, learners developed questions based on place-based observations related to their local communities. They collaboratively refined research questions and subsequently designed their investigation through online discourse with the larger community, which included peers, teachers, researchers, community members (e.g., local fishermen), and STEM professionals.

In one investigation, students studied marine microplastic pollution, collecting water samples from different locations and analyzing them using established techniques. As students filtered the samples through sieves constructed in different sizes, they recorded findings in terms of quantity and colors of microfibers and fragments of plastic.

These data were then uploaded to the WeatherBlur platform and further analyzed using web-based mathematics learning tools, with learners working in teams to create graphs and charts to answer specific questions based on their data. Utilizing WeatherBlur as a data repository, learners were also able to compare data from their water samples to data from samples from different locations. Students used a combination of online and offline resources to further examine microplastic pollution in marine food webs and effects on the environment. Based on their learning experiences, learners initiated the idea of a culminating presentation that they could share with the community and decided to make a collaborative documentary. Experts from the larger community were virtually interviewed for the documentary using Skype. In addition to presenting their documentary to a large community audience, learners also presented posters at a state-wide summit hosted by WeatherBlur, where they interacted with peers from other participating schools.

In another investigation, learners were interested in examining which organisms got caught with lobsters in traps. They utilized WeatherBlur as a platform to document details, such as the species, number, sex, and sizes of creatures caught in lobster traps, and through partnerships with local fishermen, they found a large number of invasive European green crabs as the primary bycatch. They used mobile data tools to upload, share, and comment on data in multimedia formats (e.g., numerical, photo, and video). Learners also used various web-based graphical analysis tools to help interpret and connect participant-posted data to scientific data related to climate and the oceans, such as temperature and depth of the water. This project subsequently "evolved into a green crab information exchange between students, fishermen, scientists, and community members sharing the number of green crabs caught per trap" (Kermish-Allen, Peterman, & Bevc, 2019, p. 629). Learners' contributions of data and findings supported the Governor's creation of a state-wide task force to further investigate the impact of the invasive green crab species on fisheries.

6.4.2 | CP during the WeatherBlur investigation

Examining the WeatherBlur investigations as examples of CP enables us to further explore the social and collaborative contexts embedded in the learning experience. For example, the web-based platform integrated citizen science with participant-driven inquiry, empowering learners by providing opportunities for them to pose questions based on their observations and communities. Through CP, learners were able to engage in multiple ways, posing questions on the iWonder space, for example, where they received immediate feedback from the larger community, which helped refine their questions toward inquiry of specific, investigable topics. Interactions with this larger community of peers, teachers, researchers, community members, and professionals further empowered learners to pose questions driven by curiosity and to engage with peers and experts as they collaboratively designed various aspects of their investigation. Learners were, for example, invited to engage in online discourse as members of a larger community, and were mentored by experts throughout their investigations, all of which shaped how learners participated as members of a STEM CoP. Table 5 demonstrates how various activities in WeatherBlur provided rich opportunities for CP through integration of STEM practices and computational thinking.

6.4.3 | Technology-mediated relations shape learner behaviors during WeatherBlur investigations

Technology-mediated relations were instrumental in enabling learners to engage collaboratively in STEM practices during the WeatherBlur investigations. Technology-mediated hermeneutic and alterity relations shaped how learners interacted with web-based tools to create graphs and charts using participant-posted data, and interpreted socio-scientific issues based on their analysis of these data. Learners also manipulated large data sets related to temperature of waters in

TABLE 5 Examples of WeatherBlur investigation activities with STEM practices

WeatherBlur STEM activity	STEM practices	Computational components
Examining water samples to detect microplastics/examining lobster traps to detect other organisms; discussing trends and hypotheses related to presence of microplastic pollutants/green crabs	Planning and carrying out investigations; analyzing and interpreting data	Problem-solving practices; systems thinking practices
Utilizing web-based mathematics tools to analyze data; using graphing and simulation tools to chart participant-posted data and connect with scientific data related to oceans	Analyzing and interpreting data; developing and using models; using mathematical and computational thinking	Modeling and simulation practices; systems thinking practices
Creating a documentary to raise awareness about microplastic pollutants; creating an information exchange and large database to raise awareness about the invasive green crabs	Constructing explanations and designing solutions	Problem-solving practices; systems thinking practices

the oceans. For example, as they manipulated variables related to the data, learners identified trends and proposed hypotheses related to the spread of microplastic pollutants and invasive green crabs with evolving understandings about complex systems in the physical world. The learner-technology pairing further shaped thinking along temporal scales, as learners used visualization tools to develop models and construct explanations incorporating large data sets related to oceans and climate. Technology-mediated relations, thus, encouraged learners to utilize emergent technologies toward discipline-specific STEM practices, while simultaneously engaging with technologies as social practices.

The learner-technology pairing was also instrumental in how learners generated investigable questions of interest related to their data. Technology-mediated relations shaped how the investigation was designed and conducted by a larger STEM CoP and how learners were subsequently able to collaboratively analyze a large number of data points with systems thinking practices. Technology-mediated relations also shaped how learners were able to connect STEM and civic engagement, where they were motivated to create a documentary, for example, to raise awareness about pollution in the local waters and the impact of an invasive species on the local ecosystem. Thus, through CP, learners were empowered to participate with agency, co-creating citizen science projects and sustaining their engagement through technology-mediated interactions as action- and research-oriented STEM practices.

7 | DISCUSSION AND SYNTHESIS

In this paper, we explored how CP provides an epistemological and pedagogical approach to understanding the T in STEM in K-12 learning contexts, creating collaborative learning experiences for STEM learners. Using examples from digital game-based learning and citizen science, we examined the Whypox and WeatherBlur investigations as inquiry-driven examples of CP for STEM learners and described how technology-mediated relations shaped learners' use of STEM practices as they participated as members of STEM CoPs. We now discuss implications of CP in STEM education, making a case for CP as a powerful epistemological and pedagogical approach that promotes STEM practices within a technologically-enhanced learning environment. We argue that focusing on the T in STEM through CP enables an explicit emphasis on computational and collaborative aspects of interactions with technologies in use, where the learner-technology pairing promotes scientific investigation and knowledge-building as well as positive learning behaviors and STEM practices.

7.1 | CP as an epistemological and pedagogical approach

In the Whypox and WeatherBlur investigations, interactions with technology as tools, practices, and pedagogical approaches (such as web-based tools, mobile apps, and serious educational gaming) were significant in shaping the perceptions of STEM learners in digital and physical worlds. Creating an awareness of how technologies are inherently connected to practices driving scientific investigations, CP offered learners opportunities to develop knowledge of STEM concepts and practices as they collaboratively investigated phenomena in digital and physical spaces. CP as an epistemological and pedagogical approach leveraged different layers of technology-mediated relations as STEM learners collaboratively developed skills and knowledge of concepts and practices across digital and physical worlds.

Several scholars have called for the thoughtful integration of technologies in STEM education, embedding technological tools and artifacts into curricula with intentional pedagogical approaches to maximize learning outcomes (e.g., Annetta et al., 2007; Hiller & Kitsantas, 2014; Sturm et al., 2018; Weintrop et al., 2016). CP as an epistemological and pedagogical approach integrates a wide range of technologies in STEM education as both tools and practices, with thoughtful consideration of how technologies mediate perceptions and knowledge construction. While CP provides opportunities to utilize various technologies to create learning environments that are motivating and engaging for STEM learners, the primary pedagogical strength of CP is that it requires learners to collaboratively interact with technologies, where the learner-technology pairing shapes learning behaviors through authentic STEM practices.

7.2 | CP provides opportunities for engagement in STEM practices

The Whyville and WeatherBlur investigations provide insightful examples of the potential for STEM learners to collaboratively engage in STEM practices through CP. The extended time scale for each investigation, along with the nature of the experiences being embedded within STEM curricula, contributed to the authenticity of the content and student actions. As interactive and collaborative problem-solvers, learners were empowered as designers, creators, and innovators, using STEM practices to connect conceptual understandings from their learning experiences to the physical world and communities around them. Theorizing through the examples of the Whyville and WeatherBlur investigations, we see how CP leverages technology-mediated relations toward authentic STEM learning experiences, where learners create, design, share, and explore in ways that require and emphasize interactions with technology while focusing on STEM practices. As learners evaluated information, made arguments based on evidence, and developed models to explore the spread of Whypox and the effects of microplastics as pollutants in WeatherBlur, these investigations with CP not only offered engaging collaborative learning experiences, but also empowered learner-technology interactions in ways that fostered the use of STEM practices.

CP addresses the need for integrated STEM instruction to engage learners in solving real-world problems by applying STEM practices toward finding innovative solutions to these problems (Brown et al., 2011; Kelley & Knowles, 2016; NRC, 2012) and creating multiple opportunities for learners to engage in STEM practices through discipline-specific and social, collaborative interactions. Kafai and Burke (2014) envisioned CP empowering learners by creating pathways for learners to participate as producers, consumers, and distributors of digital technologies. We extend this vision of CP to STEM education, where CP empowers learners to engage with technological tools, applying them through authentic STEM practices that mirror practices of STEM professionals, such as real-time virtual participation in ongoing STEM projects and inquiry-driven investigations into ongoing research and development efforts at the STEM frontline.

7.3 | CP empowers learning in a STEM CoP

Whyville and WeatherBlur provide robust examples of web-based platforms offering immersive STEM learning experiences designed as shared community experiences. Both Whyville and WeatherBlur offered learners a larger virtual community to interact with, which included peers, teachers, mentors, members of local and global communities, and STEM professionals. As learners engaged in Whypox and WeatherBlur investigations, learners collaborated with a subset of their virtual and real-world communities. Through these interactions, STEM communities of practice were formed, fulfilling all of Wenger's (1998) defining characteristics of CoPs. First, these CoPs centered on a shared domain of interest defined by the investigation. Students continually built community through both virtual and in-person collaborative interactions. Online discourse in both examples supported learners' participation as members of a STEM CoPs, providing opportunities for direct communication with experts and peers. Finally, learners developed shared repertoires of resources and practices focused on the investigation of Whypox, microplastic pollutants, and invasive green crabs. Through CP, individual learners developed shared understandings as they interacted with their STEM CoP in the digital and physical world. Learners' engagement with technology was firmly grounded by the shared goals, values, and practices of a larger community. Consequently, through CP, learners developed shared understandings of concepts and applications of authentic STEM practices related to phenomena being studied, with opportunities to contribute as members of a STEM CoP, adding to the shared repertoire of resources and knowledge.

8 | CONCLUSION AND IMPLICATIONS

In this paper, we explored the nature of the T in STEM, with a focus on learner behaviors and the potential of technology-mediated experiences with CP in shaping STEM learning. In particular, by de-emphasizing the *what* about technology and bringing renewed focus to the *how* associated with these technologies, we make a case for CP as an epistemological and pedagogical approach that integrates technologies as tools and practices, with a focus on how they are used in STEM practices among students and STEM professionals alike.

Emphasizing both computational and collaborative components of the learning experience, CP provides STEM learners authentic opportunities to interact with emergent technologies and with each other as members of a STEM CoP. On the one hand, technology forms an integral part of the everyday lives of learners as they increasingly engage with technological tools, devices, and practices in social contexts. On the other hand, technology-mediated relations continually shape behaviors that are central to the practices of STEM professionals using interdisciplinary and transdisciplinary approaches to real-world issues in STEM contexts. Considering the T in STEM through a CP lens provides a natural link between technology-mediated hermeneutic and alterity relations and authentic STEM practices. Therefore, as we reflect on the T in STEM, and as STEM continues to evolve as an interdisciplinary and transdisciplinary entity in education, we propose that CP be leveraged in STEM contexts toward a perspective of technology as mediating innovative, novel approaches to complex problems in the real world, with learners collaboratively engaged as members of a STEM CoP.

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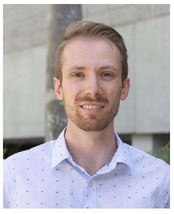
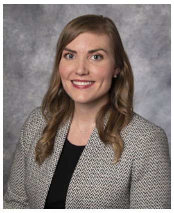
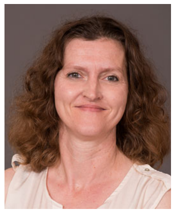
Ramya Sivaraj is a Doctoral Candidate in the Department of Curriculum and Instruction at the University of Minnesota, specializing in STEM education with a supporting minor in Learning Technologies. She has teaching experience in science and education at various levels, including graduate courses in science education, undergraduate courses in geological sciences, and eighth grade science and language arts. Her research interests include studying collaborative discourse, with a focus on epistemic or knowledge-building resources and practices in integrated STEM contexts. Her research examines how middle school students engage in epistemic practices during small group engineering design activities.



Dr. Joshua A. Ellis is an Assistant Professor of Science Education at Florida International University in Miami, Florida. His research explores the role of technology in both K-12 education and pre-service/in-service teacher education. In particular, his work has considered the role that online, blended, and technology-enhanced face-to-face learning environments have in supporting STEM learning for both students and educators. He currently serves as the Co-Chair of the Science Education Special Interest Group for the Society for Information Technology and Teacher Education and the Co-Coordinator of Strand 9: Educational Technology for the Association of Science Teacher Education.



Dr. Jeanna R. Wieselmann is an Assistant Professor of STEM Education at Southern Methodist University in Dallas, TX. Her research focuses on integrated STEM education and has explored student participation patterns in small group STEM activities. She also studies gender equity in STEM and maintaining elementary girls' interest in STEM through both in-school and out-of-school experiences. Dr. Wieselmann is interested in STEM schools, integrated STEM curriculum development, and teacher professional development to support equitable teaching practices. She is a past recipient of the NSF Graduate Research Fellowship.



Dr. Gillian Roehrig is a Professor of STEM education at the University of Minnesota. Her work in integrated STEM explores teachers' conceptions and implementation of STEM, curriculum development, and student learning in small groups during STEM lessons. She has received over $30 million in federal and state grants and published over 100 peer-reviewed journal articles and book chapters. She is a former board member of the National Association of Research in Science Teaching and former president of the Association for Science Teacher Education.

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