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Boundary Play and Pivots in Public Computation: New Directions in STEM Education*

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In this paper, we introduce "public computation" as a genre of learning environments that can be used to radically broaden public participation in authentic, computation-enabled STEM disciplinary practices. Our paradigmatic approach utilizes open-source software designed for professional scientists, engineers and digital artists, and situates them in an undiluted form, alongside live and archived expert support, in a public space. We present case studies in DigiPlay, a prototypical public computation space we designed at the University of Calgary, where users can interact directly with scientific simulations as well as the underlying open source code using an array of massive multi-touch screens. We argue that in such a space, public interactions with the code can be thought of as "boundary work and play", through which public participation becomes legitimate scientific act, as the public engages in the invention of novel scientific creation through truly open-ended explorations with pivotal elements of the code.

Keywords: public computation; STEM integration; complex systems; boundary play; open source

1. Introduction

Heidegger famously remarked that the essence of technology is nothing technological [1]. The eminent Canadian scientist and public philosopher Ursula Franklin argued that technology can be best understood not as a set of tools but as a contextually embedded practice [2]. This perspective implies that technology should be viewed not only as ways and means of performing disciplinary work, but also in light of broader norms of participation in disciplinary and ancillary cultures that develop around localized technological infrastructure. For example, while the general practice of programming can be explained in terms of generalized computational abstractions and algorithmic dexterity [3], professionals in specific disciplines often require and develop specialized programming tools and localized practices suited for their disciplinary and/or institutional goals [4]. In Heideggerian terms, this corresponds to the "frame" around technology, which, according to Heidegger, is the essence of technology [1].

In this paper, we paradigmatically argue for a frame shift in the technological infrastructure as it pertains to computationally intensive STEM and public education. We introduce *public computing* as a new form of open-ended, public learning environments, in which visitors can directly access, modify and create complex and authentic scientific work through interacting with open source computing platforms. Building on previous work by Shanahan, Burke and Francis [5], we adopt the position that authentic encounters with integrated STEM, for experts and beginners alike, involve the experience of multi-, inter- or transdisciplinarity. In formal education, the meaning of individual STEM disciplines is often formed in reference or opposition to codified forms of disciplinary knowledge and culture such as curricula, textbooks and accepted teaching and learning models. Public STEM spaces, however, can be undocked from those codified meanings creating places, technological means and human capital to explore new ways of knowing and being, offering opportunities to play with disciplinary meanings and expertise in authentic yet novel and unexpected ways. Open-source computing can further facilitate this process by opening up the "code", which often reifies epistemic and representational work of experts, for the public. The opening up of epistemic and representational possibilities, we argue, are both due the structural affordances of the computing media (e.g., open source and touch-based interactivity), as well as the opportunities of collaboration with friends, strangers and experts that often get taken up through joint action as users configure and reconfigure novel scientific representations and their explanations.

To this end, we present a paradigmatic case study, where we introduce DigiPlay: a public learning environment that uses open source computing for STEM experiences. Building on the work of Holland and colleagues [22], we present the theoretical underpinnings of our work and then describe a qualitative analysis of participants' experiences that highlights how learning in such a space can be understood as boundary work and play with pivots through the construction and re-configuration of figured worlds.

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2. Theoretical background

2.1 Modeling complexity as a context for STEM integration

The emphasis on "integration" implies that the diverse, individual STEM fields of knowledge and practice should be merged in a manner that reveals big ideas and representational practices that unify or transcend specific disciplines [6–8]. At the heart of our work is the notion that systems thinking and associated representational practices—in particular, reasoning about and modeling complex systems—can serve as a productive context for STEM integration. *Emergence* is a central characteristic of complex systems. It is the process through which unintended consequences *arise* from interactions among the multiple parts of a system. For example, larger scale patterns, such as flocks of birds and schools of fish, *emerge* from rather simple and relatively unplanned interactions between many individual entities [9, 10].

Engineering educators have argued that systems thinking is integral to engineering education at all levels because it is essential for designing engineering systems and managing the design process, which involves managing unintended and emergent consequences [11, 12]. At the K12 level, modeling complex systems has been shown to be a productive context for bringing together multiple STEM disciplines. For example, in elementary and middle school science, several scholars have been able to connect science and design through a focus on modeling complex systems by emphasizing engineering design [7, 8, 13] and computational modeling [14–16].

Our choice of multi-agent simulations as the means to simulate complexity is based on prior research illustrating that while learners at all levels find understanding emergent processes challenging [17], multi-agent-based computational models and simulations can be successful in helping them overcome the difficulties [9, 16, 18]. These studies show that curricula that utilize agent-based models can help learners understand complex systems and emergence by grounding emergent phenomena in terms of their embodied, agent-level intuitions. The ability to fluidly and meaningfully move, to "dive in" and "step out" of emergent phenomena [19], enables learners to connect their agent-level, embodied and intuitive understanding to the emergent-level outcomes [16, 18, 20].

2.2 STEM as figured worlds and boundaries

When conceptualizing science and technology as human practices, the idea of figured worlds is salient. School science, for instance, is in part the constant re/creation by students and teacher of what science is, what its practices are and what types of people are and can be a part of that practice [21]. The world of school science is what Holland and her colleagues [22] would describe as an 'as if' world, where participants become part of acting and creating a shared set of rules, norms and values that define that world. These figured worlds become cultural realms where "particular characters and actors are recognized, significance is assigned to certain acts, and particular outcomes are valued over others" [22, p. 53]. Individuals' identities and the agency they carry both constitute and are constructed by and within those created cultural realms. In academic disciplines, figured worlds can comprise interwoven sets of disciplinary knowledge and values that are used to assess each other and novices in their acts to seek entrance to or ongoing acceptance within those worlds [23]. Those specialized worlds are also always multiple and alternate: intersecting to varying degrees but never completely isolated. In any everyday or specialized experiences our identities and their figured worlds collide. For example, figured worlds of engineering education intersect with figured worlds of science, technology, university life, youth culture, being and becoming gendered and more [24]. Those intersections and contradictions are also sites of meaning making and agency, changing the nature of disciplinary educational experiences [25]. As Holland and her colleagues poignantly stated: "The space of freedom that is the space of play between these vocations is the space of the author" [22, p. 238].

Figured worlds are both durable and changeable. They are socially reproduced through ongoing communities and yet they are made and re-made through boundary and identity work. Rahm and Moore [26] for example spotlight the ways in which students' identities-in-practice in an informal STEM program create newly figured worlds of personal scientific participation, different from the formalized worlds of school and postsecondary science. That process of new figuration can be aided through the invocation or creation of counter-worlds: a world that defines only what this one is not [22]. Political speeches are strong examples where a "world we don't want" is essential to the discursive creation of the world that the candidate proposes.

These conceptions of alternate, intersecting and counterworlds and the framing of identities as social works in progress bare a strong coherence with concepts of boundary work. Emerging from the sociology of science, Gieryn [27, 28] worked to reframe the problem of demarcation (i.e., distinguishing science from non-science) from a theoretical and sociological challenge to a practical and ongoing element of scientific work. Taking inspiration from the constantly remade social and political boundaries that shape cartographies, he labelled as "boundary work" the continuous acts of figured world creation that scientists engage in when they frame their work through what it is not (e.g., "not-religion" "not-mechanics" "not this kind of research but that kind"). What is striking is the way that boundary work becomes not the work of peripheral participants, of novices seeking entry into a social world, but an act that always exists at the core of a figured world. It is central to its meaning, and therefore an essential aspect of the creation of those worlds and all participants' experiences in them.

Rahm and colleagues [29] examine a similar conceptualization in attempting to identify the meaning of scientific authenticity within a formal/informal partnership between STEM students, teachers and scientists. Their analysis breaks from the notion that disciplinary cultures must only be transferred from expert to novice, that authentic practice always begins as peripheral participation through gradual learning or simulation of disciplinary practices. They conceptualize scientific disciplinary authenticity as an emergent property, i.e., as an experience of meaning making that unfolds through negotiation between all of the participants.

Where multiple social worlds intersect, boundary objects can also become important features for negotiating and navigating between and across them. Boundary objects can be tangible (e.g., maps, [30]), textual (e.g., science news stories, [31]) or conceptual (e.g., the ecological meaning of resilience, [32]). Their primary feature is that they are meaningful in multiple social worlds, even though those definitions may be different or even contradictory. Collaborations between experts embedded in disciplinary practices can proceed, even in the absence of shared understanding and language, when boundary objects can be acted upon in ways that are meaningful to each social world [30, 33]. Similarly, Holland et al. [22], following Vygotsky [34], highlight the ways that various objects can be pivots that allow individuals entry into new and emerging figured worlds. While they focus on the value of objects for novices, we suggest that objects of various types can also become intrasubjective boundary objects, allowing individuals (novice and expert) to move back and forth, and through inter-spaces, between different figured worlds.

And in that sense, boundary work can also be boundary play. Holland et al. [22] begin with Vygotsky's notions of play in children as an entry point in understanding their roles in the various games they play in their social lives. They extend it, however, to recognize that it is a key process in the encounter with new, emerging or alternate figured worlds and counter-worlds. They focus on how people, through playful even sometimes contradictory interactions, come to create, share and participate in figured worlds. But more than that, they argue, even short term playful excursions into new, emerging and previously counter-worlds can dishabituate us from the active identities and figurations of our usual worlds, leaving players and their home worlds both transformed.

Public STEM and computing spaces, because of their multi- inter- and transdisciplinary character, offer a unique play opportunity in the boundary spaces between and among disciplines. Informal STEM educators, such as Rahm and Moore [26] have already recognized the multiplicity that even the various overlapping and intersecting worlds of scientific practice create. Others have argued that the very idea of an integrated STEM education is itself a boundary object allowing educators to re-imagine the potential of intersecting worlds through collaborative STEM practice [5]. Arguments over the meaning of STEM and its potentially integrative character have invigorated boundary work over what even constitutes STEM education. In contemporary scientific practice, driven often by large data sets and modelling [35], computing can also be understood as a world that not only exists as its own disciplinary culture and practice but also one that intersects with individual STEM disciplinary worlds [36].

Just because multiple disciplinary worlds are possible within STEM and computing, however, it is not a given that play will happen; that is, the environment must facilitate and encourage it. In classroom-based ethnographic studies, it is difficult to avoid falling into established patterns of identity and boundary work that re-create the figured world of disciplinary science in ways that reify the status quo [21]. Public spaces, removed from established curricular trajectories can make room for different interactions, where play as an expert in alternative figured worlds may be transformative. Through such forms of participation, the public may come to identify and even define how they "belong" in STEM. Fostering "belongingness" [55] can in turn greatly facilitate greater disciplinary engagement and participation, especially among non-dominant groups in STEM. Here we explore one such space.

3. Public computation: computing in public, computing for public

3.1 Public computation in DigiPlay: glass-box, open source and public

DigiPlay is a learning environment located in an indoor, public walkway at the University of Calgary. It consists of three 80″ touch screens, each powered by a desktop. The screens currently display open source simulations of complex systems. Visitors can use the touch-sensitive screens to interact with simulated visualizations of complex systems in which the larger scale patterns (flocks) *emerge* as each virtual bird performs simple interactions with neighbouring birds. The simulations are programmed using the Processing programming language and visualization platform [40]. Processing is open source, used by professional computer scientists and digital artists alike, and there is a strong online user community of experts and learners, making sample code and simulations accessible to the public.

The Processing simulations we designed for DigiPlay are both open source and "glass box" [41]. The *open source* nature of the code makes it possible for visitors to interact with and modify the code that may have been originally created by an expert, and it also allows us as developers of DigiPlay to extend and modify functionalities of the Processing programming language itself, as needed. The *glass box* [42] nature of Processing enables visitors to access the underlying code while the simulations are running, in the form of dynamic visualizations in full-screen mode, by simply hitting the "Escape" button once on the on-screen keyboard. DigiPlay visitors can directly interact with and modify the emergent patterns in the visualizations by adding new birds to the flock (by touching the screens), and at the same time they can make deeper changes to the way the individual birds interact by accessing the underlying code.

The algorithms we used are adapted from Reas & Fry's [40] implementation of Craig Reynold's classic algorithm for simulating flocking of birds (Reynold termed each virtual bird a "Boid") [43]. Each Boid in the simulation acts as a computational "agent", and the DigiPlay simulations can therefore can be understood as multi-agent simulations. The term "agent" here indicates individual computational objects or actors. It is the behaviors and interactions between these agents and elements of the environments in which they are situated that give rise to emergent, system-level behavior (e.g., the formation and movement of a traffic jam or the spread of disease). Each agent in a multi-agent simulation makes its own decision. Therefore, the emergent patterns represented in the simulations do not result from averaging over a population but from the aggregation of the outcomes of individual-level decisions of multiple agents. This concept forms the central scientific meaning of the simulations.

The rules obeyed by each Boid in the simulations are as follows: alignment, separation, and cohesion. Alignment means that a bird tends to turn so that it is moving in the same direction that nearby birds are moving. Separation means that a bird will turn to avoid another bird that gets too close. Cohesion means that a bird will move towards other nearby birds (unless another bird is too close). The relevant portion of the code that controls the relative weights of these "rules" (see Figure 1, right-hand side image), was used as the pivot to explain to the visitors both how the simulations work in terms of the agent-level rules, as well as to provide them with opportunities to directly alter the *key* interactions between the boids and thus generate new patterns of aggregate-level behaviors.

Finally, the *public* nature of the space ensures that anyone can walk in and interact with DigiPlay. The users can access just-in-time information as they are interacting with the touch screens, which provide them instructions for modifying the live simulations. The "rules" obeyed by the Boids are also explained in the form of posters on glass walls surrounding the monitors. In addition, there is often an on-site facilitator present to provide the public direct and live access to expertise. The on-site facilitator is one of the members of the team that developed the exhibit (including the first author), and they have a deep understanding of the underlying code. The facilitator's primary role is encoura-

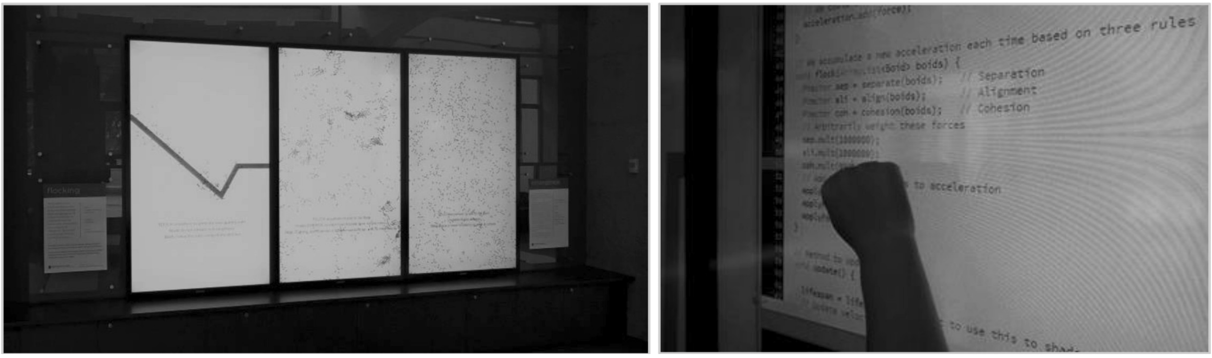

Fig. 1. The Digiplay environment (left) and a young visitor hacking the DigiPlay code (right).

ging the visitors to "hack" the simulations, showing them how to access the underlying code and pointing them to relevant areas in the code that can be easily altered to potentially powerful effect.

In using the word *public,* we are careful to engage the term as a description of the space and its materiality rather than as a noun for those involved. Even with the recognition that there can be no single "public" in relation to science and technology, the very noun itself is colonized with images of passive or resistant recipients of finalized knowledge [44]. Theorizing the descriptively public nature of this work has engaged the tradition of public pedagogy. Public pedagogy in the literal sense has evolved as a way of conceptualizing education outside of formal institutions, but even further than that often emphasizes the power of non-institutional spaces (such as media, popular culture and public spaces) rather than organized informal learning environments such as museums and zoos. It is this conception of public that we engage here, where education becomes an act that is deinstitutionalized, cultural and performative [45]. The path of learning and engagement is not set or determined by the designers but is created together in public with all who participate. This work does not intend to be an experience "for the public" in the sense of a lesson taught explicitly to outsiders, but it is STEM education "in the interest of publicness" [46] where computing can become public, bringing people (participants and designers) together in a shared experience. As Biesta argues, such work is always experimental, always changeable because it creates new ways of being, doing and experiencing. We examine here the potential for new ways of engaging in the acts of programming, modelling and interpreting STEM concepts.

3.2 Learning through boundary play: the role of pivots

As Jurow [37] demonstrated, figured worlds can be helpful for understanding how learners become engaged in simulated projects because "it provides a way to understand how students assume orientations necessary to participate in collectively imagined situations" [37, p. 39]. Holland describes figured worlds as interpretive frames, and Jurow further argued that through extended participation in a figured world, one can come to embody the perspectives within the figured world and act according to the local order. We find Jurow's analysis to be particularly aligned with our project, especially given the use of multi-agent simulations in DigiPlay. Computationally speaking, in our context, "local order" can be viewed as the individual-level rules that are followed by each of the agents. Understanding these rules is key to understanding how the patterns emerge, how to alter these patterns and how to invent new emergent patterns.

The code, therefore, plays an important role as a *pivot* [38] in the experience of the participants. Pivots are artifacts, culturally defined, that shift the frame of an activity and evoke or "'open up' figured worlds" [22, p. 61]. The elements of a figured world—its artifacts, storylines, characters and their concerns—help in positioning oneself meaningfully in relation to the figured world [22, 39]. We believe that learning in playful excursions through the use of pivots—i.e., boundary play—can help visitors move beyond their usual figured worlds (e.g., "I am not a hacker") and help them directly engage with complex disciplinary work (e.g., coding and simulating complex systems), by incorporating their intuitive knowledge and idiosyncrasies, as they learn with friends and families.

In our case, pivots are code fragments that serve as gateways for the participants. They are "high leverage" segments of code, typically consisting of a few lines, with explanations written in natural language alongside the programming commands. The high leverage nature of the code arises from the fact that small changes to the code have really striking impact on the outcome of the simulation, including its visual dynamics. Much like a toy wand can facilitate a child's imagining of a world of wizards and witches, pivots serve as entry points to more complex coding and longer term engagement with the simulation, opening up the learners' imaginations of the world of the agents and of themselves as coders. However, as our analysis will reveal, the *public* nature of our learning environment—explained in more detail in the next section—allowed for informal and unprompted collaborative interpretations of the code and for the meaning of the simulations to emerge among the visitors. Pivots, therefore, not only serve as devices for introducing visitors to the designers' figured worlds embedded in the simulations, but also as devices that can bring together new informal and formal representations (and interpretations) of scientific work.

4. Methods

The data are in the form of field notes, video recordings and photographs of visitor interactions with DigiPlay. The observed conversations reported here took place among the visitors, and are typically their interpretations of the code and the patterns of flocking behavior displayed in the simulations as they are modified.

We report our analysis in the form of two retrospective observational case studies. The first case is of a single visit by a group of three visitors, and the second case is of a visit by a group of undergraduate students in education. We chose these cases from a corpus of over 20 cases, where each "case" corresponds to a "visit" either by an individual or a group of visitors. These visits lasted on an average 10–15 minutes and were recorded through short audio and/or video clips filmed with a mobile phone. Field notes were written either live or retrospectively by both or either researcher. Because DigiPlay is housed within a university, many of these cases involve visitors who were likely affiliated with the university, such as graduate and undergraduate students. At the same time, because DigiPlay is located in a public walkway that is en-route to the University-run elementary and kindergarten schools, we also get younger visitors accompanied by parents and other adult guardians. We chose these two cases because we believed that they would be representative of at least some of the wide range of variability of visitors' ages and group composition.

In the first case, the visitors were two young school-aged boys (Sam and Rex, pseudonyms), who visited DigiPlay along with an adult (Mary, pseudonym). Their age suggested that their figured worlds of science, programming and technology might all be emergent and that the phenomenon of play may be central to their everyday interactions with the world. In the second case, the visitors were a group of six undergraduate students in education, who had no prior background in programming. The course director of these students had invited one of the authors to introduce them to the DigiPlay simulations as an opportunity to learn about STEM through playful engagement with code. Each visit lasted around 20 minutes. Our analysis focuses on a particularly illuminating segment of conversation between three students, Molly, Sally and Amy (pseudonyms) that took place midway during their visit.

We adopted a phenomenographic approach for our analysis. Our choice of phenomenography was based on Marton's argument that phenomenography deals with the forms of immediate experience as well as conceptual thought and physical behavior [47, p. 41–42]. This is particularly important for our theoretical focus on figured worlds and boundary work, which involves not only how we act in the world, but also how we conceptualize and interpret our actions and the environment where we *are* and *might be* situated. Our analysis is grounded in a "nondualist ontology": "there is only one world, a real existing world that is experienced and understood in different ways by human beings; it is both objective and subjective at the same time. An experience is now a relationship between object and subject that encompasses them both" [48, p. 537]. An object or an event, in this view, is also "seen" as the *emergent* phenomenon—i.e., "the complex of all different ways it *might be* experienced" [48, p. 113]. The figured worlds of the visitors are also emergent and dynamically constructed. Visitors' figured worlds are evident to us, albeit interpretively, through visitors' actions on the computational elements in DigiPlay as well as their interactions with others in the space.

Our analysis is thematic in nature. We rely on observations of the visitors' actions and conversations, facilitated by the recordings and field notes, as our primary source of data. To look for instances of boundary work and boundary play, we focused on the actions the visitors undertake in DigiPlay as they alter the visualizations and the code.

5. Findings

A common observation across most visitors in DigiPlay is the contrast between the original intent of particular elements of the code from the perspective of the exhibit designers on one hand and the modifications carried out by the visitors on the other. In our analysis, fragments of the underlying code therefore serve as boundary objects—pivots—between the *figured worlds* of the exhibit designers and the visitors. The figured worlds of the visitors, however, are malleable and so is the pivotal code. With the passage of time, visitors' actions on the code are further shaped by the conversations that unfold in the space among the visitors and vice versa. We chose the following cases because they illustrate vividly the interdependent and emergent nature of the visitor experience.

5.1 Code and flocks: the designer's boundary objects and figured worlds

Sam and Rex began their interactions with the simulations by touching the screens to add new Boids to the simulations, and Mary began reading aloud the "rules" obeyed by the Boids from one of the posters on the DigiPlay glass panels. After a couple of minutes, the facilitator pointed to a Boid on screen and explained to Sam and Rex that the Boids follow three concurrent rules with their nearest neighbors: alignment (turn toward the nearest Boid), coherence (move closer to the nearest Boid), and separation (maintain a minimum separation with the nearest Boid). His explanations were both verbal and gestural: he explained verbally and demonstrated through embodied movements how his body would *turn* toward (align), *move* toward (cohere) and *separate* from the nearest Boid. His intention, in doing so, was to explain how larger scale patterns, such as a flock of several Boids, can emerge from local, individual-level rules obeyed by each Boid, showing a deep embeddedness in the scientific purpose of the simulations.

The facilitator then asked Sam and Rex if they would like to hack the simulations. Sam expressed disbelief and ran away to a chair and feigned to pass out, lying down in a chair. Rex was also shocked, but both of them were excited, as evident in their jumping up and down. At this point, the facilitator pointed them to the portion of the code where they could control the relative weights of the three forces: alignment, coherence and separation (Fig. 1, right). The facilitator, who also designed the code for the simulations, pointed out that the three forces were weighted as follows: separation (1.6), alignment (1.5), and coherence (1.0).

It had taken the first author several weeks to optimize these parameters at these values, through repeated tests, given his objective of simulating flocks of birds. So, this was the exhibit designer's figured world: the code, and the resultant simulation, should realistically depict how flocks of birds form. Figured worlds rely on cultural artifacts that serve as boundary objects [22, 51], and the cultural artifact in this case was the open source code on which this simulation was based. As Cole [51] points out, cultural artifacts have developmental histories, which assume both an obvious and necessary material object as well as an ideal or a conceptual aspect (intentionality), which in this case corresponds to the multiple versions of the algorithm and the code, authored by other experts and available in open source format, that the designer compared with and adapted from. Adaptations from the original and related versions were necessary for several reasons, the primary being the geometry of the screen and the size of the Boids. As in any multi-agent simulation, these factors greatly altered the movement and density of the Boids and hence the emergent patterns or flocks. The adaptations were reflected in the choice of the numbers that act as relative weights of the three forces and are an example of the "sub-stance" of intentionality [22, p. 61] that was embedded in the figured world of intended use (as a realistic simulation) from the perspective of the designer.

Fig. 2. Rex and Sam's Boid Prison.

5.2 Boid prisons and code use: visitors' figured worlds and boundary work

For Rex and Sam, it was a lot less important to simulate flocking birds. Once they realized that they could easily make substantial changes to the emergent behaviors by altering the relative weights of the three forces, they began changing them to arbitrarily high values: separation (2300), alignment (1620), and coherence (2073). Once they made the changes and ran the simulation, Rex explains to Sam: *"They [Boids] have to come together but they also have to move far away."* Standing behind them, Mary points to the Boids getting close to each other and then turning away, and exclaims, *"Oh look they are bonking."* At this point, Rex starts tapping the screen toward the bottom left corner, and adds a lot of Boids (~one hundred), and it results in a "blob" of Boids (Fig. 2). Sam exclaims and laughs, so does Mary; Sam says, *"I love this"*. Sam then says that it looks like a "glitch" to him—meaning that this is not the behavior that he expected. At this point, Mary interjects: "*Look what you have done to them—they cannot escape . . . I am gonna call them the "swarm""*. Sam then interjects: "*I am gonna call them the 'prison'"*. Rex then says, *"Anyone who gets close to the prison, gets sucked in it"*. Mary says reflectively: "*Hmmmm"*. The visitors are all now looking intently at what happens when Rex keeps adding new Boids very close to the blob. The new Boids do indeed appear to stick to the blob, and the blob keeps growing in size, and almost no Boid escapes the blob. After several seconds of intent observation and adding new Boids, Rex explains: "*I guess they have to stay as close as possible and they have to stay away as far as possible . . . the forces of being closer are stronger"*. Mary says: "*I guess they are cohering, right? Is that what is happening?"* Sam interjects: "*The jail cell"*. Mary now responds: "*Huh . . . jail cells . . . So do you think that this model could be used to explain what would happen . . . umm . . . in . . . overcrowding in prisons?"* Sam responds: "*yeah!*". Mary then smilingly explains to the facilitator that she always tries to "sneak in" lessons on social justice.

A key characteristic of boundary objects is their ill-structured nature, allowing them to have different meanings in the different social worlds that they cross and therefore to be acted on in completely different ways [30]. This is particularly relevant in situations of cooperation without consensus or in asynchronous engagements by individuals inhabiting different figured worlds because engagement with the objects becomes dominated by localized meanings. The visitors did indeed localize (i.e., appropriate) the code and the simulation, by making simple but powerful changes to the code, and through their interpretations of the emergent patterns in the simulation. Their figured world of meaning and purpose of the simulation was distinct from that of the designers.

However, we believe that the analysis reported here also illustrates how the code serves as a pivot. From the designers' perspective, working with the code and interpreting the code is crucial in terms of supporting the intended purpose of helping the visitors learn about emergence. Working with the code pivots the visitors partially and playfully into the designer's figured worlds, and this is evident in the form of visitors' explanations of the emergent patterns in terms of agent-level rules. See for example, Rex's explanations of why the Boids are "bonking", Mary's explanation of why prisons are forming, etc. in the earlier paragraph, that exemplify this claim. Developing such multi-level explanations is the central goal of using multi-agent simulations to model complex systems [41]. However, at the same time, the visitors' figured worlds of Boid Prisons were co-constructed through joint action on the code and interpretations of how the code alterations were affecting the simulated visualization. These figured worlds—Boid prisons, jail cells, and a cluster of Boids as a model of overcrowding—were dissonant from the figured worlds (bird flocking) of the exhibit designer. Stepping back, the code may have served as a pivot allowing play between the larger disciplinary cultures of natural and social sciences in which the designer's and visitors' (respectively) figured worlds of the simulation were embedded.

Fig. 3. Sally's "high speed" Boids; Mary's "large universe".

5.3 Figured worlds across disciplines: Boids in a large universe

Molly, Amy, Sally and their three classmates began their interactions with the simulations in a similar fashion to Rex, Sam and Mary. Molly began touching the screen to generate new Boids, as Amy and her classmates took turns in reading the rules on screen as well as on the posters. The first author also explained to them, as in the previous case, both verbally and gesturally how the Boids form flocks collectively without a central leader, as each individual Boid follows the three rules of separation, cohesion and alignment. The first author then also introduced the group to the pivotal code fragment, and Sally and Molly decided to alter the parameters so that instead of travelling in flocks, all the Boids would merge into one another (i.e., cohere together and overlap on one another) and travel as one. Through trial and error, they were able to adjust the parameters in the code so that the Boids would nearly merge together.

However, the designer (first author) had also programed the simulations to "reset" the visualizations every 2 minutes. So, the visitors were unable to see the merging behavior in its entirety. To address this issue, Sally then went back into the code and asked the first author to direct her to the region of the code where she could alter the speed of the Boids. Sally was actually able to figure out the relevant region of the code by scrolling up and reading the commented out explanations adjacent to the code with very little help. She then doubled the speed of the Boids and re-started the simulation. However, contrary to her expectation, instead of merging faster, the Boids began travelling really fast in short lines of three or four, zig-zagging the screen very rapidly, without interacting with other lines or Boids (see Fig. 3).

Noticing their surprise, the first author then asked the group to explain why they made the changes and what they thought was going on in the simulation. Molly wondered if the Boids were colliding less: "*Maybe they don't collide as much . . . maybe . . . ?*". Sally interjects that the cohesive force may not be strong enough: "*Maybe the cohesion is not able to pull . . .*". Amy then joins in, and interjects Sally: "*Well . . . the chances of them hitting each other are less, because they are going faster . . .*". This seemed to make sense to Molly, who expressed her agreement: "*Yeah . . .*". Sally is still unconvinced and continues to think that the Boids should still collide, even if the chances are low: "*But they would still collide though . . . wouldn't they?*". Amy responds to Sally: "*Well . . . this is like the large* *universe*". The first author then asked Mary to explain her response further: "*Lets talk about that a bit*. . ." Amy then explained that she is also taking an astronomy class, where she learnt about the "large universe". The Large-Scale universe model [50] is a well-known theoretical model about the structure of the universe that seeks to study the organization of planetary bodies at the scale of intergalactic distances. Amy used her interpretation of this model as an analogy to explain what she was noticing on screen. She explained that the speed of the Boids was high, and the space between the groups of Boids really large, so they are not able to collide: "*I am sorry—I just did an Astronomy class*. . . *they are all*. . . *things are going so fast*. . . *and the space between them is so large ... that they can't hit each other . . . if you watch them, they are not hitting each other*. . . *I don't know [smiling gently]*. . . *I don't know more than that [laughs gently]*".

So, for Mary, the interpretive frame of the large universe from her astronomy class had leaked into her interpretation of the dynamics of Boids moving at high speed. Large universe, originally a figured world in astronomy, now becomes a figured world for understanding complex dynamics of virtual Boids. One could argue that the code and the visualization both served as pivots here. Furthermore, it is interesting to note that the code that generated this large universe was not Amy's; it was Sally and Molly's joint creation, and it was the interpretation that was Amy's. Therefore, this episode once again illustrates the collaborative and emergent nature of the discourse in a public computational space.

6. Conclusion

So how can public computation alter the status quo of STEM experiences and education? We argue that coding as public experience can be understood as the coming together of canonical disciplinary practices and private interpretations as the public engages in the playful boundary work of generating and configuring multiple figured worlds. The open source code enables public access to archived expertise, and the public nature of the environment invites and validates multiple figured worlds that would not otherwise coexist in a traditional classroom or learning environment. Our study illustrates how the experience of the public in such open and informal spaces, as well as the design of such spaces can be understood through the lens of figured worlds and pivots.

In each of the cases we have presented, a specific change in the code becomes a clear pivot in two ways. Firstly, they are pivots for the creation of a newly figured world within the simulation (i.e., a world that gives meaning to the Boids and their interactions). The prison model and the large universe model are not the worlds of the Boids until those changes are made to the code by the visitors. And those changes, because they explicitly require the visitors to rethink the simulations, draw them into the world of the Boids to imagine what it must be to be one of the agents and how the spaces between them would be experienced. This leads to the second, pivotal action: a newly figured world where the visitors are the creators of the simulation's new form and therefore acting as coders and hackers, changing the simulations for their own purposes and doing so in meaningful and productive ways. Even if it is fleeting, this is a newly figured world where they are not the recipients of instructions on how to code but are instead the owners and creators of something new and something that required interaction with the code as an expert.

As Holland et al. [22] argued, an important pivot into figured worlds is through discourses. In our study, discourse is primarily of two forms: computational code, and spoken language. It is the visitors' conversations and interpretive actions that bridge these two forms of discourse. For Bakhtin [54], as Holland et al. [22] point out, it is the dialogicality of social activity, the mutual interplay of specific instance and generic means, that results in a constant interplay between the converging and diverging forces of linguistic practices, neither of which exists apart from the other. Across the cases we presented here, these forces and their interplay are imminently visible: Mary's interpretations of Sally's code and Rex and Sam's interpretations of Boid prisons built on Mary's noticings are both examples of such emergent and interdependent discursive practices. Perhaps in the truest sense of the "public", one can no longer claim these figured worlds as private. They are truly collaborative, constructed through joint action, and extend the original meanings of the open-source simulations in a public setting.

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