

## The Role of the Physical Space in Distributed Intelligence

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**Abstract:** While technology is often the focus within learning environments designed to support distributed intelligence, less attention has been paid to the role of the physical space. In response, this symposium brings together seven research strands in which the design of the physical space is a central component of their distributed intelligences and the collaborative learning they support. Through this symposium, participants will get the opportunity to engage with these distributed intelligence designs to understand firsthand the opportunities and challenges associated with the careful integration of space in their own learning designs.

### Introduction

Distributed intelligence states that the "intelligence" of the learning environment is not held solely within the minds of students, but is distributed across the physical space and the technologies developed and deployed to support students' learning (Pea, 1993). Distributed intelligence goes further, noting that these supports are integral to the class' intelligence, by supporting specific kinds of communication, aggregation, and sharing of ideas and information, and removing any of the supports fundamentally changes the intelligence within the learning environment (Pea, 1993). Research on designing for distributed intelligence has placed significant attention on the learners and the technologies (Kim & Hannafin, 2011; Hoadley & Kali, 2019); however, there has been limited research on the role that the physical space itself plays in supporting this intelligence (Hod, 2017; Kirsh, 1995). Further, the work that has been done, has been largely fragmented (Ellis & Goodyear, 2015). In response, there is a need for opportunities to collectively examine research that critically examines the design, implementation, and analysis of physical spaces as a central component of distributed intelligence.

### Objectives

In response, this interactive symposium brings together 7 research projects as a way to provide participants multiple perspectives on how carefully considered roles for the physical space (along with technology and learners) within innovative pedagogical designs, can come together to create unique forms of distributed intelligence. Each of the presentations in this symposium will discuss how space is intentionally considered within their designs with a particular focus on: 1) The connection between the physical space, the technologies, the learners, and learning goals in their designed learning experiences; 2) The fundamental role the physical space played in their designs' distributed intelligence. Together, these contributions aim to provide an opportunity for participants to experience, synthesize, and discuss, leading approaches to spatially mediated distributed intelligence. This session will also help participants understand the unique forms of learning and collaboration that can only be achieved through designs in which the spatial elements are intentionally part of

learners' collective intelligence. Through this approach, participants will gain insight into how they may better incorporate spatial elements into their own computer-supported collaborative learning designs.

## Session Format

The symposium will begin with each researcher giving a two-minute lightning talk to introduce participants to their projects and the role the physical space plays in their designs. Next, participants will have a chance to move through the presentation space to try out versions of each project. It is important to note that these "scaled down" versions of the designs will further highlight the unique affordances and challenges of spatially mediated learning environments. The session will conclude with our discussant, Roy Pea, facilitating conversations between the researchers and participants on critical issues around the design and implementation of learning environments in which the physical space plays a central role in their distributed intelligence.

## Implications

We believe this session will provide an important opportunity for opening dialogues on an emerging, but fragmented, area of computer supported collaborative learning. It will help researchers hoping to design distributed intelligence learning environments, in which the space itself plays a critical role, to better understand their unique opportunities and challenges. In this way, we anticipate this session helping to scale up this area of research and reducing the duplication of errors and challenges encountered by experienced researchers.

## When the map is the territory: Supporting interdisciplinary collaborative learning in immersive hybrid simulations

Mike Tissenbaum, Vishesh Kumar, Taehyun Kim & Litong Zeng

While students need to learn about climate science and sustainability, they should not be decoupled from the interconnected political, economic, social, and ecological priorities that drive them (Hollweg et al., 2011). Within these interconnected systems, students also need to learn that the actions of a single city or nation are not siloed, rather they can impact their neighbours both near and far, particularly when they rely on shared resources to sustain and grow. An underemphasized aspect of these complex systems are the social interactions across parties with competing interests, requiring involved parties to balance their own needs and wants against those of their neighbors, and the strategic, political, and social ramification of their decisions.

Given their ability to emulate the complex scenarios and conditions found in the real-world, simulations and games are a particularly effective approach to supporting students in developing these complex integrated understandings. Immersive and hybrid (combined digital and physical) games and simulations, in particular, offer the ability to leverage the physical space of the classroom to embody the geographical distributions and proximal connections found in the real world. These spatially-indexed environments enable face-to-face interactions, at varying levels of privacy, which mirror the social complexities of real-world economic and political negotiations (Squire et al., 2007).

Because of the tight coupling of the physical space to the kinds of authentic interaction students engage in within these immersive simulations, their design cannot decouple the physical learning space itself from the design of the simulation, or the underlying learning content. In response, this symposium will showcase an immersive whole-class multiplayer city management game named *City Settlers*, in which the classroom transforms into a fictional shared planet on which teams of participants develop their cities. In teams situated around the room, students buy and manage buildings for their cities, and trade resources and make strategic alliances with other cities across the room. The choices students make (e.g., which resources to mine and buildings to run) can impact their own city's and those throughout the class (through the spread of pollution or the depletion of shared resources). As the game progresses, students must make increasingly complex decisions about what to do both at the micro (their own city) and the macro (the whole classroom level) levels.

As part of this symposium, we will discuss how the design of *City Settlers* has supported students to engage in new forms of emergent whole-class collaboration (Kumar et al., *in press*), and how the various technologies in the space have supported and hindered this collaboration. We will also give participants the chance to play a spatially scaled-down version of *City Settlers* to experience first-hand how the space and technology come together to support students' collaborative learning.

## Mediated goal navigation in a mixed-reality embodied learning environment

Morgan Vickery, Mengxi Zhou, & Joshua Danish

With the increasing ubiquity of technology that can support and track student movement as an input into computer simulations, there has been a similar rise in studies of how to interpret and support embodied cognition and learning (Alibali, & Nathan, 2012). In our work, we focus on how students learn in collective embodied activities: activities where students collaboratively use motion and their sense of movement to make sense of a phenomenon (Danish et al., 2020). From this perspective, it is important to understand the distributed nature of this process as individuals learn through both their own embodiment, and their shared embodied activities. For instance, in our research, where students embody particles and their coordinated motion determines their state of matter, each student might feel the energy and speed of their movement, but they also need to maintain distance between themselves and others and diverse trajectories to represent a gas.

Naturally, when looking at a group of students in environments such as this, students continuously adopt and negotiate goals for what to do next, regardless of what goal the teacher or facilitator may have assigned them. Our theoretical framework, the Learning in Embodied Activity Framework, considers not only how these goals are important for understanding learners' actions, but how their negotiation of these goals provides insight into their shared understanding and the relationship between their individual and collective ideas (Danish et al., 2020). To understand this process of negotiation through collaboration, we turned to Tissenbaum et al.'s (2017) Divergent Collaborative Learning Mechanism Framework (DCLM) and adapted it to be applicable within an embodied learning environment. This expansion is in line with the rationale behind Tissenbaum's prior work, in which he elaborated on Fleck et al.'s (2009) Collaborative Learning Mechanism (CLM) framework to acknowledge that students' goal convergence is often a product of the scaffolds that exist in formal learning environments and that, in contrast, informal and open-ended learning environments may enable students to diverge from the goals of the collective. While this expansion provides a necessary distinction of the nature of students' collaboration, we argue that embodied, exploratory, and playful learning environments within formal educational settings require an additional level of nuance.

In adapting Tissenbaum's DCLM for analysis of video data from an implementation of a mixed-reality embodied learning environment "Science through Technology Enhanced Play" (STEP) with a mixed class of 22 first and second-grade students, we developed a taxonomy for mapping students' expression of goal convergence and divergence through both their talk and embodiment. In this analysis, we use our 'Embodied-DCLM' to code for rich moments of student goal divergence, convergence, and navigation, and aim to answer the following questions: (1) What mediational means within a mixed-reality embodied learning environment enable student divergence and convergence of goals? (2) What is the impact of students' goal negotiation upon their experience learning in a collective, embodied classroom environment?

Our findings indicate how both disparate and shared goals can help to drive students towards collective understanding of a phenomenon. We will also discuss how designers can leverage an understanding of how this process is mediated to explicitly support productive goal negotiation in service of learning through collective embodied modelling.

## Young people's ethic of place-based design: Co-creating digital 'ecologies of care' for fellow residents

Katie Headrick Taylor & Kaleb Germinaro

The notion of "smart cities" implies that urban environments can learn: increased digital connectivity distributes intelligence across entire communities and neighborhoods, thus improving the well-being of residents' lives. The more digitally connected data centers are to schools, to traffic signals, to retail, to individual smartphones, the better off--the more intelligent--our environments will be. In this way, techno-solutionism characterizes the design logic for developing smart(er) cities, a logic predominantly promoted by tech companies that obscures or ignores an ethic of care for *people* and the natural world.

Our project rejects techno-solutionism and instead takes up technofeminism (Floegel & Costello, 2021) to ask what ethics young people bring to place-based, digital designs of communities, towns, and cities. Who and what do young people care about, and care for, when imagining a smarter built environment? How do young people envision their local contexts via digital mapping tools within the precarities and potentials of national and global crises? From a technofeminist perspective, the intelligence of a community or city should be "determined by marginalized community members rather than researchers [or tech companies] who make assumptions about what communities need" (Floegel & Costello, 2021, p. 5) or how much capital can be accumulated in the coffers of a few.

Across New York, Nashville, Seattle, Chicago, and a nonmetropolitan location in the Southeastern US, young people built *digital desire layers* over extant maps of their cities and towns to show how built infrastructures could be more compassionate for all residents. Because of the support learners received via a

Mobile City Science curriculum (Taylor et al., 2019), and their endemic experiences as young residents, youth enacted anticipatory approaches (Amsler & Facer, 2017) toward community development that imagined how they would like to live in the face of growing social and environmental insecurities. Mapping ideal locations for health clinics (easily accessible to sick grandparents), a “Friendship Park” (with conversation starters painted on rocks), community gardens (for children to learn how to grow food), bicycle lanes, more trash cans, and bus routes, for instance, young people anticipated the necessity of strengthening the social and relational fabric of community spaces within increasingly uncertain times.

In pursuing answers to our research questions, we situated our analysis of video records and artifacts within a qualitative GIS project in which mapping practices are rife with power and ambivalence within a given community. We found that young people used digital mapping to design and visualize their communities as *ecologies of care* (cf. Suárez-Orozco & Suárez-Orozco, 2015): places--and new connections between those places--to make life better for not just themselves but for intergenerational, multi-racial, and more-than-human configurations of residents. Unlike smart cities that prioritize efficiencies via digital connectivity, ecologies of care developed by young people prioritized intergenerational and multi-species connectivity through cleaner, safer, and more physically interactive dwellings and public spaces. Their contributions invite cities to re-imagine collective learning to be about *care at scale*, rather than intelligence at scale, in which technologies “sustain, heal, and empower our communities, as well as seek liberation from our exploitative and oppressive systems” (Design Justice Network Principles, 2018, n.p.).

## How classrooms can support learning communities

Tom Moher & Jim Slotta

In 2010, we began a project called Embedded Phenomena for Inquiry Communities (EPIC) building on a media simulation framework called “Embedded Phenomena” (EP; Moher, 2006). EP uses distributed intelligences to manifest an immersive object of inquiry. Students are asked to share the conceit that a dynamic scientific phenomenon has been geo-spatially mapped onto the classroom space. Digital “portals” situated around the room serve as location-dependent probes into the local state of the phenomenon. Students work across space and time, observing and manipulating phenomena through the portals, constructing and using models of its behavior. For example, in the *Wallcology* EP, computer monitors are placed on each classroom wall, providing a form of X-ray “wallscope” that reveals an ecosystem of animated insects, living on various surfaces (plaster, brick, hot-and cold-water pipes), and whose populations vary according to systemic variables (temperature, humidity). Statistical information about each Wallscope habitat is available on screen (e.g., population and temperature graphs). EPIC employed the Knowledge Community and Inquiry (KCI) model to guide our design of curriculum in which students collectively investigate the EP, building an evidentiary knowledge base and responding as a community to system perturbations (e.g., invasive species) (Slotta et al., 2018).

EP immerse full classrooms of learners in a shared, 'coincident' reality. While the representation is sparse (i.e., compared with modern VR), the dynamic animations and visual differences between portals reinforce the dynamism and spatial variability of the underlying phenomenon. Immersion can heighten the sense of presence—*being there*—in virtual environments, which may in turn foster interest and engagement in the activity. Importantly, situating activity in a spatial context that invites movement around the room necessarily increases opportunities for and richness of social interaction. Distributed intelligences can also be used to create responsive performance spaces for the enactment of *analogical disciplinary practice*. In the AquaRoom EP (Novellis & Moher, 2011), students investigate aquifer structure imagined to be present under their classroom floor by obtaining sample tubes, moving to sampling sites in the room, obtaining the sample, taking it to a simulated spectrometer for analysis, and recording their results on a classroom map. The physical movements and spatial reasoning required to enact this series of steps demark distinctive forms of disciplinary engagement that may help students develop understandings.

One of the important challenges of designing large-scale collaborative learning experiences is fostering students' awareness of and use of peer work and wider community knowledge. In EPIC, we use distributed devices (Large wall monitors and iPads) to “push” representations of community activity and progress. In *Wallcology*, for example, a large display continuously depicts an aggregated visual representation of an emerging food web, driven by learners' investigations of the ecosystems. Students use iPad apps to record any observations of predation events, which are then aggregated for display on the large monitor. The teacher uses these aggregates as a source of reference, guiding students to examine gaps or conflicts (Slotta et al., 2018).

Another important feature of the EPIC curriculum is the temporal aspect. Most collective spatial applications are quite short in duration - sometimes even a single class period. EPIC units run for months, with

the EP always available, any time students or teacher thought it was time to inquire. In this regard, EP emulate nature: always available for inquiry. However, they offer some distinct advantages over wild nature, in terms of the accessibility (i.e., situated within the classroom), and the control over disciplinary engagement (discrete habitats, food webs, etc.).

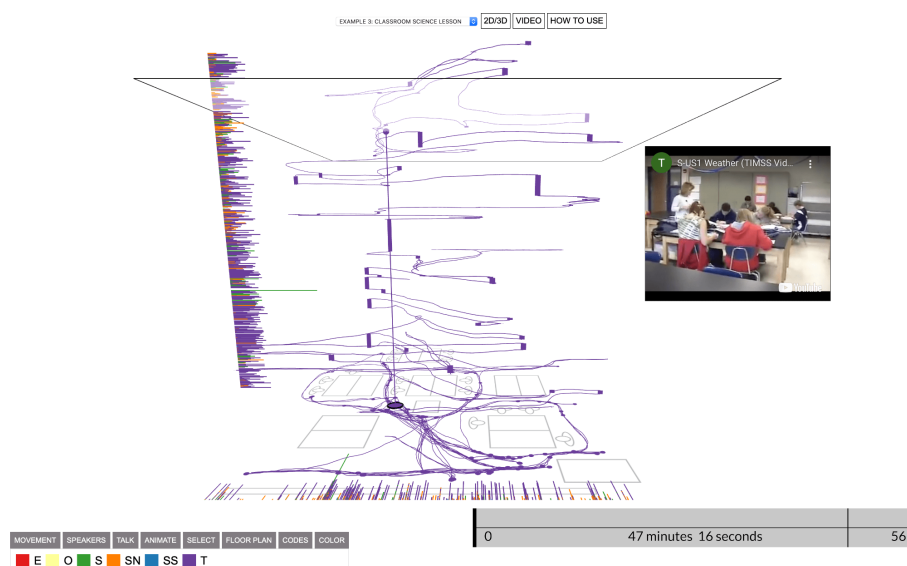
## Studying Equity Oriented & Distributed Classroom Contexts through an Interaction Geography Lens

Ben Rydal Shapiro & Sierra Gilliam

The projects in this symposium share many different and innovative approaches to pedagogical and learner-centered design in relation to the physical environment, while also asking new questions, for example, concerning the ethical collection and use of data in classroom contexts. In this presentation, we first share our efforts to expand a methodological approach called interaction geography in collaboration with teachers and teacher educators to study different equity-oriented classroom contexts (Shapiro & Garner, 2021). Subsequently, we discuss how findings from this work might contribute to and be informed by projects described in this symposium and more broadly, the notion of distributed intelligence.

**Figure 1.**

Screenshot from the IGS showing a teacher's movement (purple path where thicker parts of the path indicate the teacher is stopped) and all classroom conversation (colored rectangles where color indicates speaker) over a floor plan and a timeline that extends upwards during a classroom science lesson. This visualization provides one way to see how movement and conversation unfold over space and time. Video can be dynamically selected by interacting with this type of visualization.



We begin by providing a brief background of interaction geography, highlighting how it draws from a growing body of work that foregrounds the role of movement in learning and teaching contexts (DeLiema, Enyedy, & Danish, 2019; Marin et al., 2021). Notably, we demonstrate two open-source tools, Mondrian Transcription and the Interaction Geography Slicer (IGS), to transcribe and dynamically visualize movement and interaction in relation to the physical environment (e.g., see: <https://benrydal.github.io/igs/>). Subsequently, we describe how we are working with teachers and teacher educators to study and support teaching practice and discourse by creating interactive visualizations through these tools such as in Figure 1 depicted above.

We share findings from this work focusing on the strengths and weaknesses of interaction geography to study phenomena such as pedagogical judgment, multi-party activity, technology use, and equitable participation patterns across classrooms as well as relevant perspectives on the ethical collection and use of classroom video data. Likewise, we use these findings to consider how interaction geography can support and be informed by the many different projects in this symposium and the broader notion of distributed intelligence.

## Space Invaders: Multiple Entry Points on a Night Sky Simulation for Supporting Small Group Collaboration in Classrooms



Robb Lindgren, Nathan Kimball, James Planey, Emma Mercier & Jina Kang

Fundamental to understanding and explaining critical phenomena in astronomy is the ability to reason spatially and to integrate multiple visual perspectives (Plummer, 2014). While most astronomy instruction focuses on getting individual students to reconcile different sources of spatial data to construct canonical mental models of astronomical systems, we know from previous collaborative learning research that some of the work of integrating spatial information can occur through group activities where roles and perspectives are distributed (e.g., Colella, 2013; Hod, 2017). Astronomy education typically emphasizes observations of the night sky or the use of single-user night sky simulations, but some of the more challenging tasks, such as navigation based on star data, is benefitted by sharing and communicating across viewpoints.

Augmented reality (AR) technologies have been promoted in recent years for their ability to merge and enhance visual viewpoints in ways that are potentially productive in educational contexts (Akçayır, M., & Akçayır, 2017; Radu, 2014). AR technologies have the ability to expand and transform the physical space of a learning environment, but these transformations are usually bound to the visual perspectives of individuals with expensive headsets, and as such, the utility of AR in collaborative learning contexts has been limited. In this presentation we will describe a project in which AR is only part of a distributed technology ecosystem that supports multiple viewpoints and multiple modes of interaction with a persistent night sky simulation.

The Connections of Earth and Sky with Augmented Reality (CEASAR) platform was designed to add the component of space (literally) to small group problem-solving tasks. Students can access and annotate the same night sky simulation from a tablet, a laptop, or an AR headset such as the HoloLens 2. The diversity of access points means that certain kinds of information are privileged by different devices; the AR viewpoint, for example, affords the use of natural gestures to point and trace the trajectory of stars, whereas the tablet affords quick switching between modes such as between a view from Earth's surface to a view from outside the celestial sphere. These differences mean that students benefit from communicating with each other across viewpoints and synthesizing information to complete tasks such as calculating the latitude and longitude of an unknown position on Earth given a view of the sky at a certain point in time.

**Figure 2**

Gesture-based interactions in the augmented reality mode of the CEASAR platform.



In this symposium we will present learner data from several implementations of the CEASAR platform in classrooms, and we will give attendees the opportunity to engage with the technology in a live demonstration.

## How big was a triceratops, really? Using Augmented Reality to Support Collaborative Reasoning about Scale

Jessica Roberts & Kyle Leinart

Immersive digital environments have tremendous potential to facilitate experiential learning tasks which would be otherwise impossible or impractical in a classroom setting (Lai et al., 2020; Pirker et al., 2020). Yet despite growing enthusiasm in educational design communities for these augmented and virtual reality (hereafter collectively, “XR”) technologies, many open questions remain for how, whether, and why these technologies support learning in the K-12 setting (Cook & Thompson, 2021), particularly for collaborative learning experiences (Pirker et al., 2020). Our ongoing work on FossilVR (Figure 3, A), an immersive 3D environment in which students engage in the inference-heavy scientific processes of excavating, identifying, and rearticulating fossil skeletons in a virtual world, is exploring the affordances of XR for supporting 3rd-5th grade students in developing language and science competencies.

The prototype of our platform, built in Unity with the visual scripting language Playmaker, allowed single users to uncover fossils placed around the virtual world and record observations and inferences about

them in their observation journal (e.g., Observation: “This skull has flat teeth.” Inference: “The animal probably was a plant eater.”). Pilot testing demonstrated that learners not only enjoyed the environment but also were able to successfully use the system to generate inferences about multiple fossils.

However, the pilot revealed two key weaknesses in this single user platform. First, the aim of the platform is not only to support literacy skills but also reasoning about the nature of science. Authentic science is a collaborative practice; scientists make hypotheses based on information gathered by the scientific community over time, using new information to question and challenge prior inferences. Furthermore, viewing the fossils only in a digital, zoomable interface makes it difficult to reason about scale: how big was this animal in real life, and how did it compare to other animals in its habitat? These limitations led to the development of an augmented reality (AR) extension application (Figure 3, C) that moves the fossil exploration and annotation from the individual screen into a shared classroom space in which multiple students can inspect and annotate a life-sized AR projection. Observations are pushed to a central repository that can be tagged, sorted, and collaboratively edited by students and teachers. We hypothesized this shift can support cognitive processes more akin to those in authentic science inquiry tasks (Chinn & Malhorta, 2002). Here we report on preliminary results from interviews with teachers about design features to support collaborative learning in the classroom.

### Figure 3

The FossilVR interface (A) places students at a virtual dig site where they excavate fossils to record in the science journal (B). The Annotation Station (C) is an AR extension that places fossils at full scale into the classroom, allowing multiple students to contribute observation and inference cards to a shared platform (D).



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