Hybrid spaces for science learning: New demands and opportunities for research

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Abstract: "Hybrid spaces for science learning" refers to the merging of real and virtual worlds to produce new environments and visualizations where physical and digital objects co-exist and interact in real time. Learning science within hybrid spaces can be a fun, engaging, and reflective experience. Further, hybrid spaces are inherently social, facilitating dialogue and social exchange, as well as the construction of knowledge, paralleling the nature of contemporary science. This symposium brings together several research programs that address learning "across contexts," that span classroom activities, museum visits, and engaging, embodied experience of science phenomena. We include an international set of presenters from Canada, USA and Norway, each engaged in design and empirical investigations of designs that blends conceptual learning with the development of inquiry skills and epistemological knowledge. Each paper presents the research context, method of design and evaluation, research progress, and science learning outcomes.

Introduction to Symposium

The various disciplines of science are rapidly evolving, in part because of the infusion of new technologies and media practices, in a trend sometimes referred to as "science 2.0" (Nisbet & Mooney, 2007; Bell et al., 2007). Cutting edge technologies are increasingly used to represent data in new forms, and by means of new analytic tools, such as 3D visualizations, simulations. Social and aggregative media (e.g., Facebook, YouTube, or wikis) have also entered into the scientific realm, creating new opportunities for collaboration and exchange across disciplines and other contexts. Indeed, scientists exploring the cosmos, the oceans, and the human genome have seized upon the advantages of large, shared datasets and open lab books. While the Internet and other advanced technologies have revolutionized many facets of civilization – including science - the typical science classroom is still dominated by traditional instruction: sequences of curricular units, presented didactically, that rely on previously learned concepts, formalized testing, and teacher-student hierarchies (Krajcik et al., 2008). Our symposium represents a collection of learning science projects that are investigating how new technologies and pedagogical approaches can expand the horizons of science education beyond the space and time restrictions of the classroom, leading to powerful new ways of learning and instruction.

Hybrid spaces refer to the merging of real and virtual worlds to produce new environments for science learning. Students manipulating a physical device in a museum setting can produce changes within a digital space that, in turn, influence subsequent curricular activities. Students' social interactions online can result in changes to their physical classroom environment, or to an aggregate representation – gathered from many students and classrooms through activities in an informal setting. Observations or other data collected using mobile or ubiquitous environments can provide a source of "user contributed content" for curriculum. Students could create large shared repositories (i.e., similar to flickr) of science-related content, including social and semantic metadata that become a resource for a wide community of learners. Social networks can be used to support special interest groups or to coordinate complex pedagogical designs. Tangible and physical computing elements (e.g., multi-touch surfaces, Arduino-controlled objects, or the Microsoft Kinect) can be integrated, allowing direct or embodied manipulation of ideas. We define hybrid spaces along physical, semantic and social variables that can be used as indices for the design of new learning experiences that cut across conventional contexts.

We explore three aspects of such spaces: 1) The use of mixed reality for learning, where physical and digital objects (e.g., visualizations and simulations of science phenomena) co-exist and interact in real time. 2) Opportunities gained from digital representations of knowledge and dialogue about science that correspond spatially with student activity in physical environments, such as classrooms and science centers. 3) Understanding how the integration of informal and playful learning experiences in spaces outside the classroom (e.g. field trips to museums and science centers) can foster deeper conceptual and epistemological learning for students in the K-12 classroom.

Design has long been recognized in the learning sciences as a crucial dimension of intellectual activity, and many papers have been written about design-oriented methodologies (Brown, 1992; Hoadley. 2002). Recently, there has been an important inquiry into the nature of our design processes, which are said to capture as much of our field's learning about learning as any scientific outcomes from empirical studies. At the 2011 meeting of Computer Supported Collaborative Learning (CSCL) in Hong Kong, a new book series was announced (Chris Hoadley and Naomi Miyake, editors) that will encourage the "unpacking" and deep discussion of our designs and our design process. This perspective is particularly relevant to research of hybrid environments, which entail dramatically new forms of learning. Several years can be required just to conceptualize our environments and the kind of learning that we wish to engender, before we can conduct careful studies of learning outcomes. By way of analogy, it is challenging to develop a musical score for an instrument that has not yet been designed. Thus, we find ourselves developing the instrument first, as well as the kinds of music – the tonalities, melodies, and harmonies – that that may be suited to it. There is clearly a cyclical set of dependencies in advancing such complex pedagogical, technological and social forms of learning, in which the media are deeply part of the message. Thus, while the papers all refer to learning environments that have been developed and tested to some extent, they are all still in active design mode, and the authors have been asked to focus on their design processes and elements.

We have gathered three distinct research groups – one from Canada, one from USA, and one from Norway (with two presentations from the latter) – who have done empirical research into notions of spaces as an affordance and facilitation for interaction with science phenomena. These projects have designed and investigated learning trajectories in such spaces, paying attention to activities that span virtual and physical spaces. Our discussant, Wolff-Michael Roth, who is not affiliated with any of these research programs, will synthesize the ideas and advances in this work and lead a discussion amongst participants.

Paper 1: Science Hub: A digital medium for supporting collective science inquiry in hybrid spaces

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Across the science disciplines, the normal practices and expectations are changing in stride with the emergence of new technologies, media practices, and methodological affordances (NSF Cyberlearning Report, 2008). Bell et al. (2007) argue that the new "data-intensive" nature of 21st century science has moved scientific practices away from individual or even small groups of scientists working with individual databases and computational simulations, toward the use of cutting edge technologies to represent and analyze data in new forms, including powerful visualizations, GIS and satellite mapping, and new experimental tools and methods in every discipline. Social and aggregative media have entered the scientific realm, creating new opportunities for collaboration and exchange across disciplines and contexts, leading some to coin the term, "science 2.0" (e,g., Nisbet & Mooney, 2007).

The exciting transitions occurring in science have important implications for science education. Our research will investigate a curriculum that responds to the changing complexion of energy both as a science phenomena and a global socio political challenge in the 21st century in such a way that actually capitalize on students' digital skills, making science more engaging and at the same time preparing students more deeply for careers in science related disciplines.

We address variations and transitions between instructional contexts (Dierking et al. 2003; Rennie, 2007). In particular we address how learning in classrooms and informal settings (e.g., museums and science centers) can be mutually supportive. This paper reports on our design of a digital medium called The Science Hub (SciHub) to support student activities across formal and inform contexts, using rich, interactive media in museums, Web pages at home, and their own smart phones out on the street. The digital infrastructure is important for interconnecting these various forms of interaction, for adding a semantic layer of accessible metadata (including social networking information and patterns of use), and for enabling the design of powerful new forms of aggregated representation, real-time feedback, and pedagogical scripting.

This paper will focus on two aspects of the SciHub. First, we present our own design process, which has embodied Science 2.0, occurring across various physical and virtual contexts. We discuss our goals, constraints, guiding principles and technology systems. Second, we present a complex sequence of curriculum activities designed in conjunction with the Norwegian Museum of Science, Technology and Medicine, that engages students at home, in school and at the museum in a variety of forms of learning, including embodied activities, collective inquiry, the creation of shared multi modal resources, and the use of rich visual representations and simulations.

The SciHub is being developed to support complex patterns of inquiry that must respond to the unique contexts (both formal and informal) and configurations (individual/small group/whole class interactions) in which learning takes place (Lemke, 2000). This includes learning activities that are physically and temporally distributed, that can and should be described on multiple levels, and that engage users in emergent (i.e., not predictable, a priori) forms of learning and knowledge advancement. The description and coordination of these factors is often referred to as a "script", which includes the timing and sequencing of activities, planned moments for student reflection, and roles for students and teachers (Dillenbourg & Jermann, 2007, Hakkinen & Makitalo-Siegl, 2007).

We regard scripts as a means for specifying and making available structures, procedures, collaboration patterns, roles, materiality and resources of 21st century scientific practices, and making them relevant and engaging for learners. By embedding such scripts within a technology-enhanced environment, we can scaffold their various elements, capture the products of interactions, and provide timely feedback or input to students and teachers. Such feedback can provide participants with a visual sense of the current state of the activity, including aggregated representations from small groups, all students in a class, or everyone who has ever interacted with the script. They can provide teachers with insight into students' understandings of curriculum topics, and support classroom orchestration through evidence-based decisions (Dillenbourg, Jarvela & Fischer, 2009).

The design language of SciHub references concepts from theatrical performances, such as role, actor, script, stage, and performance. In SciHub, students contribute to aggregated products that change over time, with the products themselves serving as resources in the activity. Students cooperatively produce artifacts and experiences, challenging our notion of assessment, and adding important new dimensions of collaboration, reflection, revision and engagement. Designing research to evaluate the impacts of such activities - in terms of student learning as well as a more overarching aspect of progress for the community - has been an interesting challenge. We must consider new forms of electronic discourse that are related to building upon peers' ideas, connecting artifacts, revising documents, and interacting with physical and tangible media. Emerging notions of social and embodied learning have inspired new ways of measuring progress, capturing participation and evaluating the impact of our innovations.

Our first enactments of SciHub supported contextualization of simulations of science phenomena. Students' inquiry can be structured, or more open-ended, including a wide range of digital interactions such as logs, notes, video recordings, that are available as a resource for subsequent learning activities. Scaffolds and prompts are implemented using a system intelligence, where agents operate on content in databases, state information, proximity awareness and other parameters. SciHub activities serve to connect formal and informal contexts, with a focus on experience-based learning that takes place in the museum, and how this can be related to conceptual learning in the classroom. SciHub supports a wide range of student inputs, and can infer from sensors in a spatial environment (i.e. who is present, types of activity, location, body gestures, gaze, tangibles, mobile devices, etc.).

Paper 2: Embodied science practices in hybrid spaces

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In the Embedded Phenomena framework (Moher, 2006; 2008), simulated spatial phenomena are mapped onto the physical space of self-contained classrooms as subjects of collaborative inquiry. In prior designs employing this framework for inquiry in seismology (RoomQuake), astronomy (HelioRoom), and ecology (WallCology), access to and interaction with the simulated phenomena have been restricted to stationary "portals" (computers) strategically situated within classrooms. While these designs have leveraged embodiment in their utilization of learners' locations for perspective-taking, distributed collaboration, and enactment of analogical solutions to mathematics problems (Antle, 2009), the digital and natural worlds have remained largely parallel realities rather than hybrid spaces.

AquaRoom (Novellis & Moher, 2011) extends the Embedded Phenomena paradigm by introducing hybrid artifacts that richly problematize *physical* aspects of science practices (Reiser, 2004). AquaRoom is based on the conceit that the classroom is a small town beneath which runs a network of coherent aquifers. Children are challenged to recommend a location for a new chemical plant to be constructed within the town, with the goal of minimizing the impact of potential effluents on underground water supplies. To inform their decision, they were organized into groups to conduct a hydro-geological survey. Using the standard practice of injecting dye tracers into potential aquifer sites, they collect water samples in adjacent areas and use a photo-spectrometer to analyze the sample for presence of the dye. These analyses allow them to construct a map of the topography, direction and rate of flow of the aquifers under their "town."

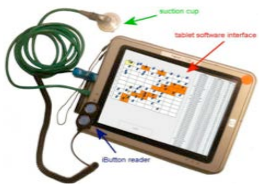

Figure 1. Portable "drilling unit."

Figure 2. Dye and sample tubes.

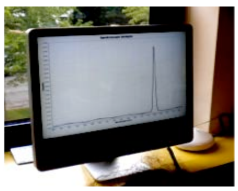

Figure 3. "Spectro-photometer."

AquaRoom blends a collection of information-carrying tangible artifacts and analogical (but information free) "props" within the learning environment. Dye injection and sample retrieval are modeled through the use of a "portable drilling unit" (Fig. 1) that includes a non-functional Ethernet cable taped to a suction cup which, when applied to the classroom floor, provides a simulated conduit for liquid flow to and from underground aquifers. Dyes are stored, and samples collected, in test tubes to which are attached special electronic caps (iButtons®), each of which contains a unique identifier (Fig. 2). Students connect the test tubes to iButton readers attached to the drilling units to effect injection and retrieval, carrying samples (in opaque collection test tubes) to a simulated photo-spectrometer (also connected to an iButton reader) to look for traces of the injected dyes (Fig. 3). Students mark up a large, shared paper grid on the wall to reflect the results of their investigations.

The design choices in AquaRoom impose physical demands analogous to those required in actual hydrogeological practice, including the selection and recording of injection and retrieval sites, physical travel to those sites, management of field instruments, collection and management of samples, use of laboratory instruments for analysis of samples, and inscription of findings (Duschl et al., 2007). In these ways, AquaRoom represents a more "seamless" model (Ishii & Ullmer, 1997) of a hybrid space than prior Embedded Phenomena, with physical actions in the real world yielding scientifically appropriate and meaningful effects in the virtual environment.

In two enactments of AquaRoom in fourth grade classrooms, we have focused on children's responses to the hybrid artifact designs, their ability to utilize the environment's affordances to conduct their investigation, their relative sense of presence within the physical and virtual worlds, and their development of understandings of effective spatial strategies for injection and sampling in the context of aquifer mapping. In our first pilot (Novellis & Moher, 2011), fidelity of representation became a prominent thread of discussion, particularly around the issue of whether correct placement of the suction cup on the floor was necessary. (It wasn't: students self-reported their locations using a coordinate system based on the room's ceiling tiles.) While opinion split on the necessity of the artifact, there was a strong consensus regarding its utility, with students citing embodied reinforcement of coordinate positions, opportunities for participation within investigative groups, and play value associated with a willing suspension of disbelief (Coleridge, 1817) in support of its use.

In a recent enactment, researchers "shadowed" the working groups to track students' practices surrounding the use of the artifacts. Students accurately placed and reported their injection/sampling locations in all but three of 176 observed cases; surprisingly, artifact fidelity did not become a subject of classroom discourse, though about a quarter of the class manifested skepticism about suction cups during post-unit interviews. Note that the students' accuracy in self-reporting their locations suggest the viability of a low-cost alternative to indoor location tracking instrumentation, at least for coarsely grained coordinate systems such as those used here. The handling of samples was similarly consistent, with only five of 217 collected samples failing to be subjected to "spectroanalysis."

Across both enactments, students showed a strong ability to transcribe analysis results to the shared map of the "town," accurately determining the aquifer topographies. Flow direction and rate (measured using stopwatches) were more challenging, but differences of opinion created opportunities for discussion of methods for resolving observational discrepancies and the practice of repeated measurements. In post-unit interviews, students almost universally were able to articulate an effective (concentric circle) inject-and-sample strategy. Analysis of student responses to the question "In your own words, please describe what we've been doing in the AquaRoom unit" showed an overwhelming predominance of "domain-oriented" (e.g., "town," "drill," "chemical plant") vs. "implementation-based" (e.g., "computer," "suction cup," "classroom") terms.

Paper 3: Designing Immersive Environments for Collective Inquiry

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This research explores how physical space, when augmented with a system of networked tablets, interactive whiteboards, and a web-based learning environment, can support face-to-face interactions as well as asynchronous knowledge co-construction. We present EvoRoom as a case study of an immersive simulation for collective inquiry. The notion of immersive simulations is not a new one, but the use of such media for conceptual learning, including the design of interactions amongst students, peers, teachers and materials, is still in nascent stages. We discuss our research objectives and our design process, as well as the outcomes from a study evaluating student perceptions and behavior within the immersive, physical simulation.

Theoretical Perspective: Recently, educators have advocated the approach of forming knowledge communities in classrooms – where members are given the responsibility to generate ideas and build on each others' ideas within an emergent, collective knowledge base (Bereiter & Scardamalia, 2003). This approach is well suited for today's science students, who must now develop collaboration and communication skills in addition to learning scientific content and procedures. In our own prior work, we have applied "Web 2.0" collaboration technologies in support of knowledge communities, connecting students with peers to co-develop a shared knowledge base (Peters & Slotta, 2010). We have also advanced the concept of a "smart classroom," where the physical environment (e.g., walls, furniture, etc.) is deeply infused with a range of digital tools and media, scaffolding students in complex pedagogical designs, through different roles and responsibilities (Lui, Tissenbaum & Slotta, 2011; Slotta, 2010).

In response to prior research in virtual worlds, such as River City (Dede, 2009) and Second Life, we now seek a layer of immersivity to transform our smart classroom into a mixed-reality immersive environment. While such virtual worlds may cultivate students' sense of ownership and play, they are fundamentally limited in terms of bodily-kinesthetic interactions, as users act through avatars via screen-based interactions (Birchfield et al., 2008). We posit that hybrid environments hold the potential to transform typical learning activities into more meaningful, whole-body experiences, promoting collaboration and a sense of knowledge community. Recent research from the Learning Sciences and Human-Computer Interaction (HCI) have advanced the notion of embodied learning, where the human mind and body are viewed as inseparable (Garbarini & Adenzato, 2004). New technologies have led to a surge of interest in augmented physical environments for hands-on and participatory learning. Examples of projects that incorporate ideas of immersion and embodiment include the Cave Automated Visualization Environment (Cruz-Neira, Sandin, & DeFanti, 1993), SMALLab (Birchfield et al., 2008) and Ambient Wood (Rogers & Price, 2004).

Inspired by these prior efforts, we seek to create powerful experiences for groups of co-located students to share and develop meaning through embodied interactions with one another and their surroundings, working a knowledge community. We added functionality for immersive simulations to our smart classroom infrastructure, where the room itself is converted into a rich simulation, and conceptual content is embedded using ubiquitous technology that supports students as they engage in carefully designed learning activities. Our research focuses on how such media and activities can support new forms of learning and instruction.

Method: In January 2011, we began a co-design partnership with a high-school biology teacher to create our immersive simulation. We considered important design elements and outlined our overall strategy. Our first design decision was the selection of an accessible topic that would allow students to gain enhanced conceptual depth and where their embodied experience would provide distinct opportunities for perception, reflection, or integration of their scientific understandings. We required a topic that was sufficiently challenging and broad enough in scope to engage students for several sessions, including introductory (i.e., non-immersive) activities. We arrived at the topics of biodiversity and evolution, which are notoriously challenging topics for teachers and students alike, and have many characteristics that would support our development of robust, engaging materials and interactions.

Figure 1. The EvoRoom immersive environment.

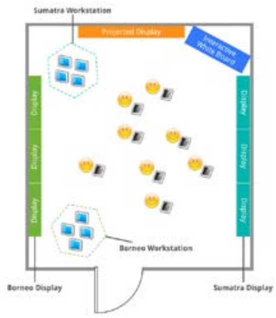

Figure 2. The smart classroom layout

As the context for students' scientific inquiry within our immersive environment, we selected the rainforest ecosystem of Borneo and Sumatra. The varied species of the rainforests offer a rich and complex ecosystem from which biodiversity may be studied, and the disappearance of the land bridges that connected Borneo and Sumatra approximately 10,000 years ago offer an interesting phenomenon through which to study evolution. This theme allowed us to develop rich, interactive media, showing various species of flora and fauna, and their interdependencies, which students can directly observe in the context of the simulation (see Figure 1). In order to support such an experience, the room is set up with multiple versions of the simulation. On each of the two long walls of the room, three projection displays are connected to form a 5-meter wide projected surface. These two wide, immersive displays on the facing walls provide a sense of enclosure. On the front wall of the room, serving to bridge these two wide displays, a single projected display provides higher-level symbolic and social information, as a resource for inquiry (see Figure 2). For all student inquiry, we developed specialized applications for tablet and laptop computers, which provided a field guide, collected student observations, and coordinated log-ins and group membership within the room. We also created specialized applications for an interactive white board to support the teacher's orchestration of activities within the room.

To support a sense of identity, each student is given a role of "ecology expert" for a certain species. They are asked to work as "field researchers" in specialized teams (e.g., primate ecologist team), with clearly delineated tasks and scientific agenda. In the biodiversity unit, students work collectively to create a food web of the ecosystem – each bringing to the activity their expert knowledge of their species. To promote connections to the rainforest environment, students create "scientific scenarios" in an introductory activity, predicting how changing one factor in the ecosystem could impact the long-term biodiversity of the rainforest. When students enter the room to find the rainforest simulated with their choice of perturbations, such that the students effectively build their own immersive environment. This helps students build identity with the materials and take ownership of their own learning.

In the evolution unit, which occurred several weeks after the biodiversity unit, students returned to the same smart classroom environment, retaining their specialty research teams, to conduct a "field visit" and survey. The teacher coordinated the activity, advancing the simulation through several historical time periods. One of the large walls was programmed to depict prehistoric Sumatra, and the other to depict Borneo in the same time period (e.g., 2 million years ago). Originally, since the two regions were connected by a land bridge, their species are identical. When the teacher advances the simulation to a more recent time period, students observe that the species have diverged! The teacher guides student observations, highlighting historical and climatological records, and drawing attention to important features of each environment,.

Findings and Discussion: In our first classroom trial, we examined student behavior and perceptions of the immersive environment using questionnaires given pre- and post-activity as well as video analysis of the activity. Students were highly engaged by the use of the tablet computer supports as well as by the immersivity of the smart classroom. Students made special note of the interactive white board application that collected and shared ideas in real-time, which allowed them to gain powerful insights about evolution. We refined the activities, and are presently enacting the biodiversity and evolution environments as part of a fully integrated biology curriculum. We have added pedagogical supports as well as visualizations to represent the community knowledge base for the duration of the curriculum. The goal is for materials to become more visible (i.e., visually rich) yet less intrusive, responding intelligently to student inputs, as well as capturing the collective wisdom of the classroom community as a resource for all participants in subsequent inquiry activities. We will report on student learning gains, interaction patterns (ie, between peers, and with elements of the environment) and next steps for research.

Paper 4: Epistemic artefacts for inquiry in hybrid spaces

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In this paper, we report on our research on the relation between physical experience and conceptual understanding, as mediated by tangible artefacts and visual representations. We explore student's meaning making as they solve disciplinary problems of their science curriculum in an inquiry-based learning environment that involves experimenting with both tangible phenomena and digital models. Drawing on perspectives on visual representations as social practice (Roschelle & Clancey, 1992; Roth & McGinn, 1998), and on socio-cultural approaches to learning and cognition (Vygotsky, 1962; Wertsch, 1998), we describe semiotic mediation as a useful framework for informing how actual (phenomenological, social, material) experience relates to the development of disciplinary knowledge. The aim of the study is two-fold. On the one hand, we aim to investigate how tangible objects and visual representations become meaningful resources in students' problem solving along an inquiry-based sequence of disciplinary activities. On the other hand, we aim to inform further development of a technology-enhanced learning environment that integrates tangible and digital experiences.

Emerging mobile and ubiquitous computing technologies have opened new possibilities for designing inquiry-based learning environments in which students can engage in embodied experimentation with simulated or augmented phenomena (Moher, 2006). In these environments, both tangible and digital objects are combined as to constitute hybrid spaces where the material and the symbolic become explicitly linked. In these spaces, both digital and tangible artefacts may become objects of, as well as resources for, inquiry. Thus, the boundaries between what can be conceived as a mere artefact and what can be conceived as a representation become blurred. In this sense, scholars have pointed out the need for theoretical accounts of the relations between physicality and representations in hybrid learning spaces (Hornecker & Buur, 2006; Price, 2008). We adopt the term *epistemic artefacts* (Scardamalia & Bereiter, 2006) in order to refer to any object, whether tangible or digital, that may serve for the advancement of discussion and coordination in a problem solving activity.

While there has been much research on visual representations as deployed in traditional desktop computers, such as multiple linked representations (Ainsworth, 2006) or interactive simulations and models (van der Meij & de Jong, 2006), few studies have investigated the role of visual representations in linking physical experiences with conceptual knowledge, or the role of physical artefacts and experience in understanding visual representations. In contrast to traditional views of visual representations as carrying meanings that are to be decoded by mental information processing, a growing body of literature points to the role of visual representations as resources for coordinating social conduct (Roschelle & Clancey, 1992; Roth & McGinn, 1998). From these perspectives, meanings are established through social, situated, material interaction, in semiotic processes by which a sign comes to refer to an object for the agents participating within given activities. This semiotic process is grounded in social interaction and is anchored to material experience.

In order to investigate how both tangible and digital objects become epistemic artefacts through social interactions, we draw on video recordings gathered from a pilot study of a multidisciplinary project that aims to develop technology-enhanced solutions for linking experiences at the school and the museum (Jahreie & Krange, 2011; Jornet & Jahreie, 2011). Using Interaction Analysis (Jordan & Henderson, 1995), we follow a group of students and their teacher as they move through a set of activities that go from direct experimentation with physical artifacts to activities involving interaction with digital models. Along the trajectory, we have observed how the meanings of the different objects and representations emerge and evolve as students together make sense of the situations they confront. The students co-construct shared empirical grounds by physically and verbally pointing and particularizing salient features of their material contexts. The students and their teacher make these categories the topic of their discussion and bring them relevant to different discourses, moving from an everyday language to more disciplinary talk. The emotional and motivational components, together with the institutional aspects of the contexts and tasks, seem to influence the kind of discourses the students adopt. The material environment, including both digital and tangible objects, as well as their own talk and bodily gestures and positions, become a complex set of semiotic resources in constant development, and which are in reciprocal relation to the participants' positions and dispositions in regard to the activities at hand. However, although both tangible objects and representational inscriptions acquire their functions and meanings through similar grounding processes, they appear to have different semiotic potentials as resources for inquiry. Implications of our findings for the design of hybrid inquiry-based learning environments are discussed.

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