Supporting Collective Inquiry: A Technology Framework for Distributed Learning

by

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Abstract

This design-based study describes the implementation and evaluation of a technology framework to support smart classrooms and Distributed Technology Enhanced Learning (DTEL) called SAIL Smart Space (S3). S3 is an open-source technology framework designed to support students engaged in inquiry investigations as a knowledge community. To evaluate the effectiveness of S3 as a generalizable technology framework, a curriculum named PLACE (Physics Learning Across Contexts and Environments) was developed to support two grade-11 physics classes (n = 22; n = 23) engaged in a multi-context inquiry curriculum based on the Knowledge Community and Inquiry (KCI) pedagogical model.

This dissertation outlines three initial design studies that established a set of design principles for DTEL curricula, and related technology infrastructures. These principles guided the development of PLACE, a twelve-week inquiry curriculum in which students drew upon their community-generated knowledge base as a source of evidence for solving ill-structured physics problems based on the physics of Hollywood movies. During the culminating smart classroom activity, the S3 framework played a central role in orchestrating student activities, including managing the flow of materials and students using real-time data mining and intelligent agents that responded...
to emergent class patterns. S3 supported students’ construction of knowledge through the use individual, collective and collaborative scripts and technologies, including tablets and interactive large-format displays. Aggregate and real-time ambient visualizations helped the teacher act as a wondering facilitator, supporting students in their inquiry where needed. A teacher orchestration tablet gave the teacher some control over the flow of the scripted activities, and alerted him to critical moments for intervention.

Analysis focuses on S3’s effectiveness in supporting students’ inquiry across multiple learning contexts and scales of time, and in making timely and effective use of the community’s knowledge base, towards producing solutions to sophisticated, ill defined problems in the domain of physics. Video analysis examined whether S3 supported teacher orchestration, freeing him to focus less on classroom management and more on students’ inquiry. Three important outcomes of this research are a set of design principles for DTEL environments, a specific technology infrastructure (S3), and a DTEL research framework.
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Chapter 1: Introduction

Imagine a classroom transformed from rows of students passively listening to a teacher lecture at the front of the class, to a space where students are moving freely throughout the room, investigating spatially indexed phenomena, and connecting to peers in dynamic emergent collaborations – a space in which the walls, floors, ceiling and furniture all become rich mediators of student-driven inquiry. Underlying technology infrastructures track emergent patterns across individual, small groups, and whole class scales, responding to pedagogical needs by providing context relevant materials and helping coordinate student movement and grouping. Ambient displays sit at the periphery of the teacher’s attention providing him detailed information on the class activities and progress, freeing him to focus on the critical task of facilitating student learning, rather than managing the classroom. With a single press on his personalized tablet the teacher can freeze the class to engage them in discussion, move them to another task, or instantly send them timely scaffolded materials. Students seamlessly move between their personal spaces on their tablets and shared knowledge spaces on large interactive displays, physically dragging information between the two, guided by carefully scripted inquiry tasks. At the end of the activity, the teacher brings up an aggregated visualization of the class’ cumulative work on a large-format display, engaging them in follow-up discussion and reflection. Finally, the teacher assigns research tasks to students for homework, which are sent to each student’s account, showing up on personalized dashboards when they log in at home. After class, the teacher reads detailed reports on student activities, gaining insight into student understanding and helping him customize next day’s activities.
With the rapid growth and adoption of personal tablets, powerful back end server computers, and high speed Wi-Fi networks, the dream of realizing such “smart” classrooms has become technically feasible; however, deeper challenges exist in realizing the development of environments that truly enable productive and effective learning to occur. This dissertation describes a design based research approach (DBRC, 2003) to the development, assessment, and refinement of such an environment, connecting it to a series of carefully designed activity scripts and a pedagogical model that engages students in inquiry tasks as a knowledge community. This chapter begins with a discussion of the motivation for this study with a focus on four main themes: (1) The social web, knowledge communities and new forms of learning and instruction; (2) Scripting and orchestrating of complex inquiry, including data mining and intelligent software agents; and (3) The development of a Distributed Technology Enhanced Learning (DTEL) environment framework to support their enactment. The chapter finishes with a description of my thesis research goals and questions.

1.1 The Social Web, Knowledge Communities and 21st Century Learning

As we as a society move further into the “Knowledge Age” (Zuboff, 2004), today’s modern workplace is shaped by new technologies and practices which are increasingly data-driven, collaborative, and predicated on a set of fundamental skills commonly referred to as information literacies (Livingstone, 2008). This change is particularly pronounced across STEM (Science, Technology, Engineering, and Math) disciplines, where workplace practices have shifted towards more data intensive practices and large, multidisciplinary collaborations over increasing spatial and temporal scales (e.g., the human genome project, global warming weather pattern tracking). This transition, sometimes referred to as science 2.0 (Gray & Szalay, 2007), highlights
the need for the integration of such practices into science education and classrooms in general. A recent report, published by the National Science Foundation, warns that a failure to better integrate these technologies and practices into science and math curricula could seriously hinder students’ ability to become productive members in a modern technological society (NSF, 2008). The need for this integration is compounded by students’ own experiences with these highly connected and social (Web 2.0) technologies outside of the classroom. Through a myriad of products and practices (e.g., Facebook, YouTube, Flickr), students are adopting new roles as producers, commentators, and classifiers of the products of their interactions, and participating more directly in the construction and organization of their own knowledge (Dohn, 2009). Such user-created content can take on many different forms, from collections of user-contributed artifacts (e.g., Flickr, YouTube), to community generated social spaces (e.g., Facebook, ResearchGate), collaboratively generated and edited evolving content (Wikipedia), and newsfeeds or other socially filtered resource streams (e.g., Reddit). Even games and leisure spaces are now deeply infused with social components (e.g., World of Warcraft, Fantasy Sports). There is evidence that this “User Contributed Content” (Vickery, 2007), encourages deeper engagement with the content and the community, due in part to users seeing themselves as participating in the community’s progress (Tedjamulia et al., 2005), and at least partially because of the awareness of “having an audience” (Wheeler, Yeomans & Wheeler, 2008). Despite the clear connection between students’ lives outside of the classroom and the skills required to succeed in future careers, the adoption of these practices in regular classroom practices lags far behind these other settings (Buckingham, 2007).
1.1.1 Socially Constructed Knowledge and Knowledge Communities.

One approach that has been advanced to respond to these challenges is that of knowledge communities (Brown & Campione, 1996; Scardamalia & Bereiter, 1994). Similar to the Web 2.0 practices described above, in knowledge communities students have ownership over the developed knowledge and its resulting artifacts (Brown, 1988). Unlike traditional learning environments, in a knowledge community, students approach learning as a collective endeavor (rather than an individual one), focusing on the development of a shared knowledge base that serves as a resource for students’ collaborative inquiry activities around authentic real-world problems (Slotta & Najafi, 2010; Bielaczyc & Collins, 1999). Technology plays a central role in knowledge communities, by scaffolding student interactions between the knowledge base and their peers. In many cases, these scaffolding technologies must be specifically designed in order to support pedagogical patterns that could not otherwise be achieved. For example, Knowledge Forum was designed as a direct response to the inability of existing off-the-shelf technologies to support Knowledge Building practices such as allowing students to make connections between objects in the knowledge base, or to use those objects as “epistemic artifacts” to serve in the further advancement of the community’s knowledge (Scardamalia & Bereiter, 2006).

Despite the seemingly tight fit between knowledge communities and the development of 21st Century STEM competencies, there has been relatively little uptake of them in the broader educational landscape. This is in part because knowledge communities put a high load on teachers, requiring them to radically change their classroom methods and the substantial time (sometimes years) required for teachers to develop the pedagogical knowledge needed to successfully enact a knowledge community curriculum (Slotta & Najafi, 2010). This is
particularly true in domains with substantive demands for content learning, such as secondary math and science, where teachers do not feel that they have the luxury of encouraging their students to work as a knowledge community and to define their own learning objectives (Slotta & Peters, 2008).

1.1.2 KCI – A Scaffolded Approach to Knowledge Building.

In response to the challenges of making the knowledge community approach more accessible to teachers, Slotta and his colleagues have developed the Knowledge Community and Inquiry (KCI) model. KCI specifies a set of design approaches to support knowledge communities in secondary science, in which students collectively work on contributing, tagging, and improving content in a shared knowledge base, which serves as a resource for subsequent inquiry (Slotta & Najafi, 2013). Within a KCI curriculum inquiry activities are designed to engage students with targeted content domains and to produce accessible outcomes. The progression of inquiry within KCI is carefully designed to allow students some flexibility and autonomy in the growth of community knowledge, but ensures progress on relevant learning goals. This flexibility is essential to allow for the emergence of new ideas and the development of a community voice. KCI also guides the design of complex inquiry activities that span multiple student configurations (individual, small group, and whole class) and contexts (in-class, at home, in the field). KCI curriculum requires a substantive epistemic shift away from didactic presentation of content (where students work largely under the guise of individual learners) and toward a collective understanding of progress and activity. Within a KCI curriculum, technology plays a vital role in its enactment, as students use technology-enhanced materials, tools, and interactive simulations to support their exploration and development of ideas.
1.2 Scripting and Orchestration of Inquiry Learning

Curricular designs that include student-contributed content and integrate rich inquiry environments are likely to be more complex and dynamic than we have seen in previous generations of computer supported learning (Slotta, 2010). Designs must support the configuration (and potentially dynamic reconfiguration, based on emergent class patterns) of students groups and activities, the technologies used, and specific teacher roles (Tissenbaum & Slotta, in press). Given that even in traditional classroom settings, when left to their own devices, students struggle to choose the most appropriate strategies, understand activity goals, or the nature of the task (O’Donnell & Dansereau, 1992), these challenges become even more pronounced in complex inquiry designs. It therefore becomes imperative to carefully design the structure of the tasks, roles, goals, and interactions patterns in the form of pedagogical “scripts” (Kaplan & Dillenbourg, 2005). These scripts can have both a long-term aspect (the overall curriculum design), and short-term aspects (the design of the individual activities that comprise the larger long-term script – Tissenbaum & Slotta, 2012). These scripts must support not only the content but also varying levels of social interaction (Hakkinen & Makitalo-Siegl, 2007).

The enactment of such scripts, especially during real time activities, can place a heavy load on teachers, as they must simultaneously manage changing student roles and groups, assign activities, and organize materials – including potentially large and diverse community-generated content from the knowledge base (Tissenbaum & Slotta, in press). The process of supporting teachers in the successful execution of these scripts is often referred to as orchestration (Dillenbourg, Jarvela & Fisher, 2009). The development of effective approaches and supports for orchestration is a complex undertaking and has been highlighted as one of the “grand challenges”
for Technology Enhanced Learning (TEL) researchers (STELLAR, 2012). In developing orchestral supports for teachers, designers must deal with the parallel tensions of reducing the teacher’s “orchestral load” (the amount of information the teacher must simultaneously receive, process, and act upon – Dillenbourg, 2012), while keeping designs flexible enough to respond to emergent ideas, themes, and avenues for investigation across multiple social planes (individual, small group, and whole class – Slotta, 2010; Stahl, 2013).

In addition to providing the teacher insights and tools that reduce his/her need to consistently focus on procedural information, there is a need to design tools that allow the teacher to understand the state of class knowledge and interact with and adjust the script in response. Often termed “orchestration technologies” (Tchounikine, 2013) these tools provide the teacher with the flexibility to change the scenario at any time, moving students through particular phases of the script, having them repeat a phase, or skip a phase depending on the class’ learning needs. Depending on the state of the class the teacher may also inject new elements into the script, such as scaffolding resources, new taxonomical elements, or tasks (e.g. class polls, or multiple choice problems). Teacher orchestration supports can be designed for both public and private interfaces (i.e., on a personal tablet or on a public interactive display). It is therefore critical when designing orchestratable technologies to consider the kinds of interactions that are supported by public (where students can observe, and potentially take part in the orchestral moves) and private (where the teacher has total control and insight into the orchestral moves) controls over the script.

1.2.1 Data mining and Intelligent Agents.
In complex and evolving knowledge communities, managing and making meaningful connections between resources in the knowledge base can quickly become an orchestrational challenge for teachers and students. One common approach to reducing this orchestrational load is through the use of metadata (i.e., data about data; Wiley, 2000), which can be both user-generated or system-generated. User-generated metadata often takes the form of tagging, where participants assign keywords to objects within the system (e.g., photos, videos, narratives, or other users). These user-generated tags can provide a powerful avenue for connecting seemingly disparate pieces of information within a community’s knowledge base (Anderson & Whitelock, 2004). System-generated meta-data can be generated automatically to capture complex underlying information about both the users of the system (e.g., assigned roles, group memberships, times logged into the system), and the products of their interactions (e.g., created artifacts, votes cast, pages visited) that can be used to coordinate access to materials and activities, assign groups, and support other logical functions of the system (Simon et al., 2004; Zhao & Okamoto 2011).

This metadata can be further leveraged for the orchestration of class activities through the implementation of “intelligent software agents” – small, active software elements that can process this underlying metadata and respond to current contexts, past actions of participants, and perform real-time data mining operations (Brusilovsky, 2001). What makes these agents particularly compelling for inquiry learning is that although their roles within the script are carefully designed (e.g., sorting students in the room to work with peers they haven’t previously worked with), who (or what) will satisfy the agent’s conditions cannot be known a priori, rather
they emerge during the script’s enactment (requiring the agents to process information in real-time – Tissenbaum & Slotta, in press).

1.3 Developing a Technology Framework to Support Complex Inquiry

In order to address the orchestrational challenges required to enact the KCI model, we needed a flexible and adaptive infrastructure that could respond to emergent patterns of student responses and support collaborative activities that include spatial, social, and semantic dependencies. A primary objective of this dissertation research is thus concerned with the development of an open source technology framework that supports: (1) individual students, small groups, and whole class progression through scripted curricular activities; (2) the management of student grouping and placement within the physical space of the activity; (3) the delivery of materials based on placement within the script, including logical dependencies and emergent community ideas; and (4) teacher orchestration scaffolds, including insight into students’ knowledge and direct control over script progression. Known as SAIL Smart Space (S3), the framework came about as a direct outcome of the studies reported in chapters below, and was predicated around the development of several constituent forms of technology:

1.3.1 Scaffolded inquiry tools and materials.

In order for students to effectively engage in inquiry activities as a knowledge community, there is a need for tools and interfaces that allow students to generate ideas, build consensus and interact with peers. Networking these tools together allows for task-specific materials and scaffolded instructions to be provided to students at the individual, small group, and whole class levels (Roschelle & Pea, 2002). Such tools (e.g., personal digital tablets) have been shown to be
highly effective in improving classroom coordination, communication, and the organization of materials (Zurita & Nussbaum, 2004). Personal handheld devices can empower students, although they may introduce the risk of curtailing interaction and collaboration due to their limited screen size (Pea and Maldonado, 2006). On the other hand, larger shared displays (such as interactive whiteboards) can facilitate collaboration by promoting shared interactions, and awareness of the contributions and actions of others (Liu & Kao, 2007). It is therefore critical to understand how specific technologies can support desired interaction patterns across multiple levels.

1.3.2 Tangible, embodied, and immersive supports for inquiry.

The proliferation of small, networked computing devices has opened up the possibility for transcending the traditional keyboard and screen paradigm of the past. With the introduction of technologies such as the iPhone and SMART boards, students can now drag, pinch, and slide digital information as if they were real objects. The Microsoft Kinect can track user movements in three-dimensional space, allowing them to wave their arms or move their bodies to interact with virtual objects. Physical computing platforms like Arduino provide novel new ways for designers to connect physical objects to digital spaces. As the computer begins to “invisibly” blend into its social and physical surrounds (Wiser, 1994), we are witnessing exciting opportunities for students to embody their learning (Dourish, 2001), and tangibly interact with the “digital bits” of their knowledge communities.

A promising new approach to supporting embodied student learning is by digitally embedding the phenomena under investigation in the walls, ceilings, and floors of the physical learning environment (e.g., the classroom or in a museum). Examples include a simulated ecology of bugs
living in a classroom’s walls (Moher, 2006), an evolutionary simulation of rainforest fauna and flora over millions of years (Lui & Slotta, 2013), and a forest augmented with sensors, speakers, and visuals displays (Price & Rogers, 2004). By bringing the physical space more deeply into play, we provide students the opportunity integrate “physicality” into their “brains-on” learning (Price & Rogers, 2003).

1.3.3 Locational and physical dependencies.

Just as the physical space of the room can help serve to index (i.e., spatially) the inquiry scenario, it can be similarly leveraged to help orient student inquiry activities. By mapping representations of students’ collective knowledge base to the physical space of the room, we can customize and contextualize the information, reducing its overall informational load (Oh & Woo, 2009). These “topological representations” can have a powerful effect on supporting student inquiry, reasoning, and argumentation, which are important for establishing co-reference and attentional alignment in collaborative learning (Roschelle & Pea, 2002). Individual student devices (e.g., tablets), also afford unique opportunities for leveraging students’ locations within the room in support of complex inquiry designs. For instance, a student’s location within the room could allow for the formation of ad hoc groups (connecting students to peers who are co-occupying a particular location or “zone” at the same time). Members within these groups could be given specific roles, duties, or subsets of information, further facilitating opportunities for inquiry or collaboration. Intelligent agents could play an important role in making such locational and physical decisions on the fly by responding to emergent class patterns, making automated decisions about what information to present to individual students or groups, or directing students where to go in the room.
1.3.4 Ambient representation supports.

One challenge faced by teachers in collaborative inquiry curricula is the need for efficient classroom management at multiple social and temporal levels (Dimitriadis, 2012). In order to support the teacher as a facilitator of student learning rather than a class manager (Hmelo-Silver, 2004), we need to develop technologies that can reduce the amount of time the teacher needs to spend focused on procedural tasks (e.g., timing of tasks, tracking students in the room, knowing the state of each students’ progress in the activity). One approach that has shown promise is the use of ambient representations. The role of ambient representations is to provide critical information for both teachers and students at the periphery of their awareness, allowing them to attend to other tasks and to only focus on the representations when needed, or when time allows (Ishii et al, 1998). Previous research has shown that such ambient tools can be effective in reducing orchestrational load (Alavi et al., 2009). Because each member of the community has different procedural information needs, the use of intelligent software agents can help in customizing the type and timing of these ambient representations across both public (e.g., large format displays – Zurita & Nussbaum 2004) and personal displays (e.g., individual tablets – Tissenbaum & Slotta, 2013).

1.3.5 Distributed Technology Enhanced Learning (DTEL) Environments.

When examined together, the various Technology Enhanced Learning (TEL) approaches described above require a rethinking of how the community’s intelligence is distributed within and across the knowledge community (Dede, 1996). Similar to Lave & Wenger’s (1991) and Brown, Collins & Durgid’s (1989) notions that student learning is contextually situated, Pea
(2004) argues that a community’s intelligence is similarly situated within and distributed across the physical spaces, artifacts, and technologies in which the community’s learning takes place. For instance, the dynamic visualizations, simulations, and social and pedagogical scaffolds that support students in their learning are essential for establishing co-reference within the community (Pea, 1994). As such, the community’s intelligence does not reside within a single mind (Hollan, Hutchins & Kirsh, 2000; Hewitt & Scardamalia, 1998), and the underlying scaffolds cannot be simply removed or “faded” away, as they are an intrinsic part of the community’s learning and intelligence. Pea calls this “spreading” of the community’s knowledge across the spaces, tools, scales of time, and participants as Distributed Intelligence (DI; 2004).

Within increasingly rich and complex learning designs there is a growing need to understand how the models of Technology Enhanced Learning and Distributed Intelligence can be seen as synergistic complements to each other in supporting students engaged in inquiry as a knowledge community. In response, we suggest a model in which technological, social, spatial, and temporal elements are carefully considered in the design of curricular scripts for knowledge communities engaged in Technology Enhanced Learning, which we term Distributed Technology Enhanced Learning (DTEL). Below I outline my research questions, which aim to understand the role that a DTEL environment can play in supporting rich community driven inquiry.

1.4 Research Questions

This work introduces a new paradigm of learning and instruction in which conceptual, pedagogical and social variables are situated within a physical learning environment (i.e., the
classroom) and are also distributed across the members of the community, the technologies that support their learning, and multiple learning contexts. This paradigm came about in response to the need to support the complex pedagogical approaches required by KCI, to engage students as a community around authentic inquiry topics. In order to understand the potential of distributed learning environments to support new forms of learning and instruction, as well as their role within a broader inquiry curriculum, we require a reference implementation of these technologies (situated within an appropriate curriculum) upon which to establish successive cycles of design, enactment, evaluation, and re-design. To this end, my research questions investigate such a design, along two central themes:

1. Pedagogical: How can a Technology Enhanced Learning (TEL) environment support the pedagogical requirements of distributed, collective inquiry?

   a. What specific pedagogical forms and structures should be supported by TEL environments to support distributed and collective inquiry?

   b. How can such environments help make the products of a knowledge community relevant, meaningful and accessible to students, in a context sensitive way?

   c. How can TEL environments support and distribute learning across locations and contexts?

2. Orchestrational: How can DTEL environments support the enactment of knowledge community and inquiry curricula?

   a. What is the role of the teacher in a DTEL environment?
b. What forms of orchestration support can the teacher gain from the environment?

c. What orchestrational roles can intelligent software agents play in a DTEL environment?

d. How can DTEL serve to augment the physical environment in support of orchestration?

These two themes are interdependent, as one cannot design orchestrational supports without careful consideration of the pedagogical goals and requirements. Similarly, curricular designs must take into account the particular affordances and constraints for orchestration provided by the DTEL environment.

1.5 Design-based Research

Since Ann Brown (1992) first advocated for the shift of educational research away from “canned” laboratory experiments to the study of authentic “real-world” learning and instruction, many researchers have advanced the method of “design-based research” that investigates the nature of learning in its natural contexts, with all of the complexity and messiness it entails (Barab & Squire, 2004). To investigate learning “in the wild,” research must respond to the emergent features of the setting, which typically precludes the possibility of any “control” group for comparisons (DBRC, 2003). Design-based research advocates, in which design, research, and practice happen concurrently, has demonstrated considerable potential (Wang & Hannafin, 2005). A critical aspect of design-based research is that a design is not a static object, but is continuously or periodically inspected, evaluated, and modified in response to what is working and what is not (Collins, Joseph & Bielaczyc, 2004). The outcome of design-based research is a
rich narrative of the implementation process and an inspectable artifact that can help us inquire more broadly into the nature of learning in complex systems and to refine generative or predictive theories on learning (DBRC).

Sandoval (2004) and Slotta (2013) have both observed that DBR produces an abstract design (i.e., before any enactment) that could be analyzed in terms of its adherence to or reification of a theoretical perspective. The design of learning environments can be guided by theoretical conjectures about how to support specific forms of learning in a given context. A design-based approach makes these conjectures explicit, allowing them to be empirically refined or rejected. This refinement can lead to not only the improvement of the learning environment, but also refinements in the learning theory itself (Sandoval, 2004).

For this reason, design-based research is particularly important to my thesis work. While the KCI model allows some specific conjectures about how a DTEL can support community-based or collective inquiry, these can only be tested and explored by first building and testing out such an environment. Through the design and implementation of one working DTEL environment, I can investigate the research questions above. By developing the pedagogical and orchestrational elements and observing how they worked (i.e., what forms of interaction and learning occurred) it is possible to evaluate the role of DTEL in supporting KCI specifically, as well as more general aspects of collaborative inquiry.

1.6 Researcher Background

As an undergraduate student of Finance and Management, I became interested in the transformational effects of technology in connecting people around the world, reducing barriers
of communication, and fostering diverse yet tightly coupled communities of interest. As a result of these interests, I pursued a master’s degree at the Faulty of Information in order to more deeply understand how such networks were designed, how to support the informational needs of members within these communities, and how individuals’ participation within these digital communities was blurring the lines between the digital and physical notions of self and identity. It was during this time that I met professor James D. Slotta, who challenged me to think about not just the design of these community networks and the individual changes that were occurring among members, but also how and why people learned collaboratively within such spaces, and how this could translate to more formal contexts, such as K-12 science instruction.

Shortly after joining Professors Slotta’s research group, we were given access to a small room at a local high school (a bit too small to be a full-sized classroom). This room provided a unique opportunity to rethink the design of social collaborative networks for learning that spanned both physical and digital spaces. I was very interested in thinking about how we could reimagine the design of the learning space – beyond the traditional notions of students sitting in rows with a teacher at the front of the class – into a dynamic learning space where students and teachers move about the classroom meaningfully, and the classroom itself supports and responds to this movement. I became interested in the ideas of design-based research and co-design (Penuel, Roschelle, & Shechtman, 2007) – methods that provide avenues for stakeholders – researchers, technologists, and teachers – to be deeply involved throughout a project’s lifecycle. Driven by my past experiences of working in the business and management theory I understood the value of getting all of the stakeholders to buy into and take ownership of a project, and I felt these two
avenues of learning sciences research fit my own personal philosophies for project design and execution.
Chapter 2: Literature Review

2.1 Knowledge Communities

As society moves further into the “Knowledge Age”, the everyday skills and competencies required for success in the modern workplace are being radically redefined (Zuboff, 1988). In general, the daily practices of individuals in these workplaces are increasingly more data-driven, collaborative and dependent of a set of skills commonly referred to as digital literacies (Livingstone, 2008). This change has been particularly pronounced in the disciplines of Science, Technology, Engineering, and Math (STEM), which have shifted from individual or small groups of scientists towards large multi-disciplinary teams working on large shared data-sets and simulations, over increasingly wide temporal and spatial scales (Gray and Szalay, 2007). Despite this shift in workplace practices, there has yet to be a meaningful corresponding change in traditional classroom settings (Buckingham, 2007; Collins and Halverson, 2010).

One approach to addressing the need for fostering 21st Century knowledge skills in the classroom is that of knowledge communities (Resta & LaFrierre, 2007; Slotta & Najafi, 2010). Knowledge communities are a radical shift away from traditional classroom practices that focus on rote memorization of facts and teacher led, didactic teaching methods (Scardamalia & Berieter, 1994). Instead, knowledge community approaches to learning and instruction are fundamentally learner centered (Barab, Makinster, Moore et al. 2001) and aim to engage students in independent and group research focused on real-world problems (Hakkarainen, 2002) or topics of consequence to the community (Brown & Campione, 1996). By investigating these authentic problems students both “learn to learn” (Bielacyc & Collins, 1999; Hoadley & Pea, 2001) and
come to see themselves and their work as part of a larger civilization wide effort to advance the frontiers of knowledge (Scardamalia & Bereiter, 2006).

Within the learning science community, there have been several prominent strands of research that have advanced the notion of knowledge communities including Knowledge Building (Scardamalia & Bereiter, 1994), Progressive Inquiry (Muukkonen, Hakkarainen, & Lakkala, 1999), and Fostering Communities of Learners (Brown and Campione, 1996). These researchers have suggested some fundamental design features for supporting knowledge community models in education, including fostering a collective epistemology, the development of a shared knowledge base, and the importance of reflection and discourse (Bielaczyc & Collins, 2006; Slotta & Najafi, 2013). Below, I discuss several of these design features, provide examples of how different models attempt to implement them, and close with the challenges of successfully implementing them within a knowledge community model.

2.1.1 Fostering a Collective Epistemology.

Unlike traditional classroom settings, where students are focused on their own individual learning and achievements, in knowledge communities the pursuit of knowledge is a collective endeavor (Scardamalia & Bereiter, 2006; Bielaczyc & Collins, 1999). Despite its stark contrast to traditional school approaches, the notion of a collective epistemology is much more closely aligned to the practices of the modern knowledge society workplace (Slotta & Najafi, 2013). Similar to collaborative efforts in professional science labs and cutting edge technology firms, in knowledge communities students see themselves as a collective whole, working towards a joint goal (Barab et al., 2001, Hakkarainen, 2007). A critical epistemological shift is fostering the understanding among students that making their own knowledge freely available gives rise to
and supports the development of new knowledge within the community (Scardamalia & Bereiter, 2006) – an approach that is widely embraced within the software community through the open source movement (Weber, 2004).

In order for students to see themselves as active members of the community, they need to feel that they have agency in the development of the community’s driving questions, learning goals, and methods for addressing and resolving them (Engle & Conant, 2002). This “turning over” of the high-level processes that define students’ approaches to inquiry and knowledge building is one of the foundational principles of Knowledge Building (Scardamalia & Bereiter, 1991). In this way, students collectively define the issue at hand (i.e., problematizing of the subject matter), what they know or believe they know about the issue, what information they need to address the issue, and how they can get the necessary information. The aim of imbuing students with a sense of “epistemic agency” is to engage them in intentional learning, wherein students are self-driven to achieve a cognitive objective beyond simply doing well (i.e., from a grades perspective) in school (Scardamalia & Bereiter, 1994).

As students collectively endeavor to solve these driving questions the growth and fostering of expertise plays a vital role. Similar to Vygotsky’s (1978) Zone of Proximal Development (ZPD), students learn in a knowledge community by interacting and sharing knowledge with community members who bring a diversity of skills, interests and expertise (Bielaczyc & Collins, 2006). This diversity of expertise can help encourage the development of varied solutions, courses of actions, and points of view within the community. In FCL, students are placed in groups that seek to develop and share (i.e., with other groups) expertise in a particular subset of a topic of inquiry (Brown, 1997). These expert groups are then broken up and re-grouped with one member
from each of the other spheres of expertise (termed a “Jigsaw”), which then collaboratively tackle a larger “consequential task”. Although different pedagogical models may approach the formation of expertise differently, its development and use as a resource is central to the community’s continued growth and sustainability.

2.1.2 Developing a Shared Knowledge Base.

In order for students to build on the ideas of their peers and to share their own expertise, there is a need to develop a centralized and accessible knowledge base for the community. In Scardamalia and Bereiter’s (e.g., 1994, 1996) Knowledge Building Model, students are tasked with populating the knowledge base with conceptual artifacts in the form of written notes. Students collaboratively work on these artifacts towards achieving epistemic goals such as knowledge advancement, idea improvement, and developing deep knowledge of the problem (Tarchi, Chuy, Donoahue et al., 2013). Similarly in Progressive Inquiry (Hakkarainen, 2003), students use the collaboratively constructed knowledge base as a space for regularly refining their driving questions and to re-evaluate hypotheses imitating the practices of scientific research communities (Muukkonen et al., 1999).

In FCL, the knowledge base is constructed through an iterative process of research and sharing of ideas and information (Brown, 1997). Through this process, students come to rely on the information of their peers in order to complete the consequential task. In particular, the Jigsaw approach employed by FCL implicitly requires students to collaboratively leverage their individual expertise of the community, as no one member has all the required information. Making the individual and collective products of the class available to all aids in facilitating a
collective epistemology by helping newcomers to adopt the discourse patterns, values, belief systems, and goals of the community (Brown, 1997).

Although each of these models varies in the level of structure by which students develop the knowledge base, they share the principle that all student contributions must be valued by the community as a resource for advancing knowledge growth (Scardamalia & Bereiter, 2006). Additionally, in each case the knowledge base is not a static resource, but is steadily evolving and being negotiated by members of the community (Slotta & Najafi, 2010). As a visible and articulated resource for community members, the knowledge base provides an avenue for students to assess their individual and collective knowledge growth (Bielaczyc & Collins, 1999) and to inspire further progress (Slotta & Najafi, 2013).

2.1.3 **Reflection and Discourse.**

Despite the general agreement among educational researchers on the importance of reflection for students in learning science, it is not always incorporated into instructional practices or curricular designs (Davis, 1988). In knowledge communities, reflection plays a central role in externalizing student conceptions (Muukkonen et al., 1999), providing opportunities for reexamining and revisiting one’s own understandings and views (Johnson & Aragon, 2003; Baird et al., 1991), and increasing students’ awareness of how they learn (Slotta & Najafi, 2013). Unlike in processes such as self-explanation (Chi, Leeuw, Chiu, LaVancer, 1994; Chi, Bassok, Lewis, and Glaser, 1989) where reflection is simply spoken without record, in knowledge communities, reflection is often recorded in notes and other persistent artifacts (such as videos, images, or posters). This process of integrating student reflections into the community’s knowledge base
makes student thinking visible and accessible to themselves, their teachers, and their peers for further knowledge work (Davis, 1998).

Discourse around the co-constructed artifacts within the knowledge base is also a powerful means for promoting community learning. Within a knowledge community, the focus is on discourse among students rather than to students (Sherin, Mendez & Louis, 2004). In FCL, students engage in cross-talk, an activity where they present the current state of their research to the rest of the class and other students have the opportunity to ask questions of fact, clarification, or extension (Brown & Campione, 1996). Discussion, analysis, and comparison of different views within the community can highlight misconceptions, gaps in understanding, and can lead to new ideas and avenues for investigation. At its core, discourse in knowledge communities is focused on cooperative development of shared knowledge, mirroring the kinds found in authentic scientific communities, such as laboratories or research meetings (Scardamalia & Bereiter, 2006).

2.1.4 Challenges in Implementing a Knowledge Community Approach.

Despite the generally recognized value of the knowledge community approach for supporting students in authentic inquiry practices, the approach has not been widely adopted by teachers (Slotta & Peters, 2008). Even when implemented, there are significant challenges to their enactment. Mintrop (2004) describes one study in which four teachers attempted to enact an FCL curriculum in their social sciences classrooms. Despite design meetings spanning several months leading up to its enactment, none of the teachers were able to enact a curriculum that adhered to the central principles of FCL. Two of the teachers, who enacted a curriculum around the issues of immigration, had significant difficulties coming up with “Big Ideas” that would translate to
students’ everyday realities. This resulted in the overall curriculum descending into a series of “chunked” units of which the Big Ideas were only an afterthought. Further, many of the activities in which students were placed in Jigsaw groups fell into patterns of students simply “doing their part” of assigned worksheets, without the substantive discourse and sense making of peers’ ideas that is at the core of the Jigsaw approach. Part of this failure to properly enact the Jigsaw can be attributed to the challenge for teachers to follow all of the discussions happening in a classroom at once, in order to get an overview of the progression of student ideas (Muukkonen et al., 1999). The challenge for teachers to maintain the “conceptual complexities” of a knowledge community design often results in simplifying the task, falling back to traditional forms of teaching, or in designs that on the surface “look” like student-centered constructivist ones, but in truth do not support authentic student inquiry (Mintrop, 2004).

Whitcomb (2004) faced similar challenges in implementing a knowledge community in three English classes in which the teachers declared “state of emergency” and ultimately abandoned the planned curriculum. Despite having designed the curriculum prior to its enactment, the failure to specify the finer points of the curriculum, and some teachers’ unfamiliarity with the content, caused them to reduce the design down to the enactment of only one or two of the “steps” of the FCL model. The teachers also found it very difficult to find relevant materials to launch and sustain the research process – a legitimate and reoccurring challenge in the implementation of FCL (Whitcomb, 2004). This lack of resources, coupled with the challenge of moving to student-centered dialogue, was a significant departure from the teachers’ traditional practices and contributed to the teachers’ sense of “emergency.” In the end rather than change class practices to fit the knowledge community model, the teachers changed the model to fit their
prior patterns of instruction (Tyack & Cuban, 1995). Whitcomb (2004) points out four ways teachers tend to subvert a learning model to fit their existing patterns: (1) Renaming of the old approaches to match the practices of the new model (e.g., video lectures as benchmarks); (2) The isolation of one aspect of the model (e.g., only implementing a Jigsaw); (3) Plan and retrench, where teachers do plan to enact the model but retrench into old practices once the curriculum is implemented; (4) and through “Fusion”, where the teacher blends aspects of the model with more comfortable, established, and traditional practices.

This need for teachers to radically change their learning practices not only creates barriers for the adoption of knowledge community approaches, but also requires significant training and practice by the teachers, often spanning multiple years and interventions. Hakkarainen (2007) points out that in similar designs, classrooms where teachers had multiple years of experience in conducting PI significantly outperformed those in which the teachers did not. This is supported by Mintrop’s (2004) findings that novice teachers required significant external direction by an experienced mentor in order to design an FCL curriculum, and even then failed to successfully enact it. These challenges become even more pronounced in advanced topics like secondary science due to their challenging conceptual domain and heavy content expectations (Slotta & Najafi, 2010). Overall the successful enactment of knowledge community models requires a high demand for resources for their design, implementation, and evaluation (Slotta & Najafi, 2013).

2.2 Inquiry-Based Learning

A similar strand of research that attempts to connect student learning to real world practices and personal experience is that of inquiry learning (Marx, Blumenfeld, Krajcik et al., 2004; Slotta & Linn, 2009; Kuhn, Black, Keselman & Kaplan, 2000; Bybee, 2004). Inquiry-based learning was
first set forth by John Dewey (1902, 1916), as response to the prevailing approaches to instruction at the time, which divided and fractionized the child’s world in stark contrast to natural flow of experiences and learning that took place outside of school. Dewey envisioned the child as the center of the learning process and advocated an active learning process where students learned from the experience of “doing” authentic tasks. Dewey argued that by connecting lessons to the child’s life and his or her expanding consciousness and growing from past experiences, there was no need to “trick” the child into being interested in learning (Dewey, 1902).

This approach to learning was most clearly seen in the development of the Dewey School (1896-1903), a laboratory school of the University of Chicago, where students engaged in practices similar to real-world everyday professionals (Meyhew & Edwards, 2007). Based on Dewey’s idea that intelligence developed in connection with the needs and opportunities of action, the Dewey School situated activities around occupations rather than the conventional notions of subjects. Students learned through the continuing or consecutive occupational activities – children learned math by running a “store”, or sewing and cooking based on their jobs within the broader community. Within the Dewey School, this learning was also tightly coupled to the notions of the community and the skills learned by students were worked out by the “cooperative efforts” of the community in response to challenges arising from everyday tasks (Meyhew & Edwards, 2007).

Despite being lauded as a major shift in educational theory, Dewey’s approaches are not without their critique. Schon (1992) notes that Dewey was unable to explain how the methods of the natural sciences are different from those of common sense inquiry (everyday practices), nor was
Dewey able to satisfactorily differentiate the kinds of rigor appropriate to each. Similarly, Schon points out that Dewey, by avoiding an objective basis for describing what is problematic with a situation and what is determinate for its resolution, never fully confronts the ontological differences in our ways seeing situations and what we construe as problematic. Bereiter (1992) similarly points out that children’s learning may be fleeting if their learning is only focused on solving real world in-the-moment problems. In other words, once a problem is solved, there is no need for further inquiry into the topic, what remains is merely an isolated set of tools for a particular task – this is in stark contrast to the deep and coherent understandings that models such as Knowledge Building attempt to foster.

Although problem-based learning is prevalent in the domains of secondary science, because of the high content expectations, problems are often focused on curricular learning goals that are linked to disciplinary knowledge – rather than the practical problems advocated by Dewey (Peters, 2010). In order to support students in progressing through inquiry driven problems, many researchers advocate for the development of scaffolds to guide students’ learning (addressing many of the issues outlined by Schon above). Below, I discuss the notions of scaffolded-inquiry and in its use in science education.

### 2.2.1 Scaffolded Inquiry.

Because students tend to generate low-level factual questions and struggle with the more systematic aspects of collaboration (Krajcik, Blumenfeld, Marx et al., 1998), within the literature on inquiry-based learning there is substantial focus on the use of scaffolds to help in guide student learning (Linn & Eylon, 2011). Inquiry scaffolds can take on many roles including facilitated reflection and discussion, access to repositories of data, and guidance through
sequences of activities. Many scholars have investigated technology-enhanced forms of
cognitive and social scaffolding. For example, computer-learning environments have become a
prominent way of providing these scaffolds to students, as exemplified in WISE (Slotta, 2004),
BeGUILE (Sandoval & Reiser, 1997), Zydeco (Kuhn, Cahill, Quintana & Soloway, 2010),
CoLAB (Savelsbergh, Van Joolingen, Sins et al., 2004), and ThinkerTools (White &
Frederickson, 1998). ThinkerTools, for example, provided students with interactive computer
simulations (around models of force and motion), analytic tools for analyzing their results, and
carefully designed reflective processes in which they evaluated their own research and that of
their peers. The ThinkerTools environment was designed to guide students through a progression
known as Inquiry Cycles, in which levels of scaffolding were gradually removed until students
were able to conduct independent inquiry around questions of their own choosing. In WISE, a
browser based inquiry environment, all the curricula and assessments are collaboratively
authored using specialized authoring tools, allowing for the creation of customized inquiry
projects around specific content and learning goals (Slotta & Linn, 2009). Because students are
scaffolded through the curriculum steps by the WISE environment, the teacher was free to
circulate within the classroom interacting with small groups of students.

Through the implementation and evaluation of these various learning environments several
frameworks for implementing scaffolded inquiry projects have been developed, including a
framework for supporting metacognition in online inquiry (Quintana, Zhang & Krajcik, 2005),
the Inquiry Cycle (White & Frederickson, 1998), and Knowledge Integration (Linn & Hsi, 2000;
Slotta & Linn, 2009). Because of the range of approaches and inquiry models, scaffolded inquiry
has received considerably larger attention from the research community in comparison to
knowledge communities (Slotta & Peters, 2008). However, despite several successful research projects and frameworks for supporting the design and enactment of scaffolded inquiry, its widespread uptake in everyday classrooms has yet to take hold. Similar to the knowledge community approach, this can be attributed in part to the need for teachers to significantly change their approach to teaching and instruction (Anderson, 2002). Inquiry learning approaches also require a significantly deeper investigation of the content material, which can require a greater time commitment from teachers who are already struggling to cover the board mandated curricular content into their existing schedules (Songer, Lee & Kam, 2002).

2.3 KCI – A Scaffolded Approach to Inquiry Learning in Knowledge Communities

Although scaffolded approaches such as WISE and ThinkerTools have found somewhat higher success in their adoption into regular school curricula, they present themselves as fine-grained “complete packages” of learning, often of shorter duration (4-6 classes), which are inserted into teachers’ broader curricula. This contrasts the attempts of other inquiry approaches, such as those by The Center for Learning Technologies in Urban Schools (LeTUS - Tal, Krajcik & Blumenfeld, 2006), to produce the larger whole curricular reforms. On the other hand, projects such as LeTUS that have attempted to implement large-scale systemic inquiry curricula have found little persistent success, due in part because of the heavy demands placed on the teacher in learning the pedagogy, and the lack of structure in the ways in which students construct and answer their big questions (Blumenfeld, Fishman, Krajcik et al., 2000).
In order to address the challenges facing knowledge community and inquiry-based learning approaches, Slotta and his colleagues (e.g., Slotta & Najafi, 2010) have developed the Knowledge Community and Inquiry (KCI) model (Figure 1). KCI attempts to address the calls for comprehensive classroom reform advocated by inquiry investigators while leveraging the finer-grained scripting of scaffolded approaches. As such, KCI is a scaffolded-inquiry model that specifies a set of design principles for a knowledge community approach for learning (Slotta & Najafi, 2013).

In KCI, students work collectively, contributing, tagging and improving content in a shared knowledge base that serves as a resource for subsequent inquiry. Inquiry activities are carefully designed so that they engage students with targeted content and provide assessable outcomes, allowing students some level of freedom and flexibility but ensuring progress on the relevant learning goals. KCI curriculum requires a substantive epistemic shift away from didactic presentation of content (where students work largely under the guise of individual learners) and
toward a collective understanding of progress and activity. KCI guides the design of complex inquiry activities that span multiple student configurations (individual, small group, and whole class) and contexts (in-class, at home, in the field). Within a KCI curriculum, which typically spans weeks or months of class time, students explore and develop ideas using technology-enhanced materials, tools, and interactive simulations. These activities are carefully scripted in order to address specific learning goals, however the script itself must be flexible enough to allow for the emergence of new ideas and community voice. As part of the development of KCI we have established a set of design principles that guide the creation of individual, cooperative, collective, and collaborative scripts and activities, and how these are scaffolded (Slotta, 2013):

- **Principle 1.** Students work collectively as a knowledge community, creating a knowledge base that is indexed to a specific content domain. Students are scaffolded to work collectively and in parallel, building upon each other’s contributions (e.g., co-editing a wiki). In KCI the inquiry is not ill defined, with students building a knowledge base on whatever appeals to them (as in discovery learning); rather, the science content expectations are used as an explicit index to focus the collaborative construction of a relevant and accessible knowledge base.

- **Principle 2.** The knowledge base is accessible for use as a resource as well as for editing and improvement by all members. Within a KCI curriculum, the knowledge base is not a static product; rather it evolves with the community and becomes a collaboratively constructed and validated resource. As students contributed and refine the community’s knowledge it becomes a reflection of the growth of the community itself, and students rely on it as a source for information, discussion, and debate. Within KCI
students should be able to contribute to the knowledge base outside of traditional classroom contexts, whenever and wherever an opportunity to contribute to the community’s knowledge growth presents itself. Students should not be limited to a single type of contribution (e.g., text-based notes), instead they should be encouraged to compile a wide array of multimedia (e.g., images, simulations, video clips or probe data) to support their inquiry.

• Principle 3. Collaborative Inquiry activities are designed to address the targeted science learning goals, including assessable outcomes. Inquiry learning is inherently constructivist, where students build upon their existing ideas to build scientific understanding. Both the long-term and short-term scripts within a KCI design must scaffold students in the collaborative development of artifacts that address the science content expectations, using the community knowledge base as the resource for their creation. This scaffolding must include the design of specific tools, materials, and prompts to help guide the students in their artifact development. The resulting artifacts must also be accessible and assessable by the teacher, for feedback and follow-up discussion with the class.

• Principle 4. The teacher plays a critical role in orchestrating the pedagogical script and adapting its execution in response to emergent ideas and avenues of inquiry. In KCI, the teacher’s role is that of an expert collaborator or mentor, responding to emergent student ideas, and orchestrating the pedagogical flow of activities. Teachers are not relegated to a “guide on the side”, left to watch the unfolding activities within the classroom, rather within a KCI script the teacher is empowered through specific, scripted interactions with
students or responses to materials, such as providing feedback and making
“consequential” orchestral decisions based on the content of student interactions and
artifacts. A KCI script includes specifically designed “intervention points”, where
teachers can make decisions about the progression of tasks, the kinds of materials that
students receive, or the composition of student groups both on-the-fly and between
activities. It is therefore critical within a KCI curriculum to give teachers deep and
context relevant insight into the state of student knowledge within the class, and the tools
to properly make these orchestral moves.

To date, KCI has been successfully implemented at the high school levels for biology (Peters &
Slotta, 2008; Lui & Slotta, 2013), earth sciences (Najafi & Slotta, 2010; Slotta & Najafi, 2012),
and grade 5-6 life sciences (Cober, Slotta & Moher 2013).

2.4 Scripting of Complex Inquiry

Curricular designs that include student-contributed content and integrate rich inquiry
environments are likely to be more complex and dynamic than we have seen in previous
generations of computer supported learning (Slotta, 2010). Designs must now include the
configuration (and possibly the dynamic re-configuration, based on emergent metadata) of
student groups and activities, the technologies used, and critical roles for the teacher. Even in
traditional classroom settings, when left to their own devices, students often struggle to
effectively collaborate, choose the most appropriate strategies, understand the goals, or the
nature of the task (O’Donnell & Dansereau, 1992; Rummel & Spada, 2007, Weinberger et al.,
2005). In order to help deal with this complexity, many researchers have advocated for the
development of pedagogical scripts which can help students by segmenting the learning
processes into more cognitively manageable phases (Kirschner, Strijbos, Kreijns & Beers, 2004). These scripts can further help guide students through complex inquiry tasks by providing instructions on the formation of student groups, the distribution of roles, the phases of work, the timing of the activity, and expected deliverables (Dillenbourg, 2002).

2.4.1 Long-term and short-term scripting.

Because inquiry-based learning curricula often span multiple weeks or months, the corresponding scripts need to be designed to accommodate multiple scales of time, student configurations, and contexts (Lemke, 2000). In order to accommodate varying granularities of the script, there is a need to develop both a long-term script, that describes the overall curriculum and timing of individual activities (e.g., a field-trip, or a homework task); and short-term aspects, that specify the individual activities at the fine grained detail of specific materials, tools and learning goals (Tissenbaum & Slotta, 2012). The design of both the long- and short-term scripts must address the content of the learning domain, including the specific learning goals for students. In one example of a scripted curriculum called Learning by Design (LBD – Kolodner, 2007), middle-school students engage in project-based inquiry to determine the effects of different balloon engine characteristics on the distance a “vehicle” would go. As part of the larger long-term script, students engage in several main activities spread out across the curriculum including a “launcher unit”, the design and conducting of experiments, Poster-Sessions, Pin-Up Sessions, and Gallery Walks. Within this long-term script, specific discourse activities are inserted at times when peer feedback might help in achieving the project challenge. Each of these activities is micro-scripted (what Kolodner calls classroom scripts) into smaller commonly repeated activities: (1) Group Presentation; (2) Teacher led Discussion; (3) Content
Focus; and (4) Reasoning and practice focus (Kolodner, 2007). Findings from this work show that students who engage in long-term and short-term LBD scripts, consistently participate more and with better quality than non-LBD science students in science practices and discourse.

### 2.4.2 Student grouping and configurations.

Within and across these scripts, there is a need to understand how students are interacting with one another while creating artifacts, developing ideas, or completing tasks. Dillenbourg and Jermann (2007) describe these various social configurations as “levels of activity” and describe five configurations that students may move between, each consisting of a larger granularity of interaction: The individual phase; the group phase; the class phase; the community phase; and the world phase. An important part of the design of curricular scripts is to ensure that the granularity of the task (i.e., the work that needs to be done), matches the granularity of the student configuration (Lemke, 2000), as a poor fit between the task and student configuration may significantly hinder student learning.

Scripting also serves to formalize student roles within the different group configurations. In reciprocal teaching, students take turns being assigned as the discussion leader, and are given specific tasks within the script that include raising questions about the content of the text and proposing new predictions for upcoming texts (Palinscar & Herrenkhol, 2002). The scripting of group configurations also allows for materials or facets of knowledge to be spread around group members, requiring them to engage in productive collaboration in order to solve tasks (similar to expert Jigsaws). In *Alien Contact* (Dunleavy, Dede, Mitchell, 2009), each member of a group received a different piece of digital data about an alien artifact (e.g., a spaceship wing), which they had to share amongst their group in order to determine its significance.
Some researchers argue that there is a need to understand the information processing strengths, weaknesses, preferences, and styles of students when configuring groups in order to ensure productive outcomes (O’Donnell & Dansereau, 1992). However, at the outset of some scripted activities this level of detailed information on group dynamics may not be available. It therefore becomes necessary, within the enactment of more complex and dynamic scripts, to provide means for capturing and processing information on individual and group performance in order to facilitate the reconfiguration of groups – either by the teacher or the system itself. Such “real time” orchestrational processes would be quite challenging for teachers on their own, as they would need to process huge amounts of student interactional data (e.g., responses to assessments, preferences, or patterns of engagement) in order to determine how to re-group students or assign appropriate materials.

2.4.3 Degrees of coercion.

When designing pedagogical scripts, there is a need to consider how much student behavior is constrained during its enactment. Dillenbourg (2002) describes the level by which students are constrained to a specific formalism as the “degree of coercion.” Although it is a continuum, he specifies it along a spectrum from induced scripts, which implicitly convey the designers expectations for problem solving and interaction, to follow-me scripts, where students are unable to escape the script and each move and answer are carefully structured and limited in their scope (e.g., a set of multiple choice or Likert questions). A script that uses little or no coercion has a high degree of freedom but also results in high levels of variability and idiosyncrasy (Kirschner, Beers, Boshuizen & Gijselaers, 2008). This can result in varying levels of collaboration, patterns of discourse, and developed artifacts. On the other hand too tightly coerced interactions can
make students feel like the lesson is “on-rails” and can result in reduced student motivation (Rummel & Spada, 2007). The design of pedagogical scripts must therefore take into account the particular goal of a given activity, and how similarly aligned interactions among and across groups and individuals need to be, in order to facilitate future scripted interactions. Highly coerced scripts, such as multiple-choice problem sets or class polls, can be highly effective tools to easily compare and contrast class answers towards progressing discussion. On the other hand, brainstorming sessions require a lower degree of coercion in order to allow students to develop ideas and to feel ownership over the final product.

2.4.4 Technologies for scripting support.

The enactment of such carefully designed scripts can be scaffolded with computer-based learning environments such as WISE (Slotta & Linn, 2009), or with scientific experimentation environments such as Molecular Workbench (Xie et al, 2011) or Vlab (Tsovaltzi et al., 2008). The use of technology can support students by automatically connecting them to required resources (including multi-media artifacts like videos), and moving them through each phase of the script as they complete the previous one. Although theoretically this allocation of resources and script progression could be done without the help of technology, its use can make the process “smoother” and reduce the load on the teacher in tracking the state of every student in the classroom and their individual resource needs (Nussbaum, Alvarez, McFarlane et al., 2009). Many of these technology platforms provide teachers with authoring environments, allowing them to determine the order in which activities are enacted, the types of discourse that students engage in, and group configurations. An example of this is the authoring environment for WISE, described above, in which a teacher can specify the number and type of activities that student
pairs engage in, the level of scaffolding (coercion) applied to the task, and the kinds of supporting materials that are available to students (Slotta & Linn, 2009).

2.5 Orchestration of Classroom Scripts

The enactment of complex technology supported inquiry scripts, especially during real time activities, can place a heavy load on teachers, as they must simultaneously manage changing student roles and groups, assign activities, and organize materials – including potentially large and diverse community-generated content from the knowledge base (Tissenbaum & Slotta, in press; Dimitriadis, 2012). The process of productively supporting interventions throughout the enactment of both short- and long-term scripts and across multiple social levels is generally termed orchestration (Dillenbourg, Jarvella, Fischer, 2009). Unlike scripting, which deals with the structuring of activities before they are run, orchestration is the regulation and management of an activity once the activity has begun (Soller, Mones, Jermann, Mueh, 2005). The orchestration of a script introduces a level of flexibility, allowing group configurations, materials presented, and even the next steps of an activity to be adjusted or “re-scripted” depending on emergent patterns, the community’s voice, or new and interesting avenues for investigation and inquiry. Particularly within the context of CSCL classrooms, the orchestration of students, materials, roles, and goals has been acknowledged as a major research design challenge (STELLAR, 2011).

2.5.1 The role of the teacher in orchestration.

The orchestration of class activities puts the teacher back into the center of the learning process as an important actor – not as a knowledge provider, but as a ‘conductor’ orchestrating a broad
range of activities (Koller et al, 2011). This becomes particularly important in inquiry-based curricula, as the teacher must be able to assess student progress, collaboration, and growth of ideas in order to make timely and context relevant adjustments to the script (Sharples, 2013). This “regulation loop” (Dillenbourg et al., 2011), allows for a more student-centered approach to the enactment of the curriculum, with the teacher intervening only where necessary. Given the wide range of factors that he or she has to attend to both during and between live activities, this shift to an orchestrator of class activities, rather than a director, can place significant pressures on them. Mitigating the “orchestrational load” (Dillenbourg, 2012) placed on teachers is a significant challenge for learning designers, and one where technology supports have shown considerable promise.

### 2.5.2 Technologies for orchestration.

Technology can play a pivotal role in orchestrating classroom activities by offloading the workflow between activities allowing the teacher to focus on the more immediate concerns of monitoring group activities and helping students or groups in need (Dillenbourg, Jarvella & Fischer, 2009). These technologies can also manage the kinds of information teachers are presented with by customizing alerts, aggregated views of student work, or giving insight into the state of the class’ knowledge. In many cases, without technology supports, this information would either be invisible or excessively time consuming for teachers to compile for themselves. These technologies generally take on two distinct but complementary forms: Orchestration Technologies and Orcheerable Technologies (Tchounikine, 2013). Below, I describe each in detail and provide examples of their use in support of classroom activities.
2.5.3 Orchestration technologies.

Orchestration technologies directly support the teacher in managing the activity (Dillenbourg et al., 2011). For example in Edunova (Roschelle, Rafanan, Estrella et al., 2010), students are sent fractions problems on their handheld devices to collaboratively solve in small groups. As groups submit answers, the teacher (on his own personal device) sees a color coded matrix letting him know if the students got the answer right on the first try (green), within a specified number of tries (yellow), or if they failed to get the answer right within a specified number of tries (red). Given this detailed information the teacher is able to enact formative assessments and adapt his instruction in response to specific student needs. While this type of orchestration tool provides the teacher with specific insight into the state of the class, it does not require the teacher to take action, nor does the system itself take action, rather it gives the teacher better information to help him or her make decisions. Other orchestration technologies aim to automatically manage the learning setting through the use of data mining or other software logic, freeing the teacher to focus on the core issues (Tchounikine, 2013; Tissenbaum & Slotta, 2014).

One avenue of Orchestration Technologies that has shown a growing interest in recent years is that of ambient technologies. Ishii et al. (1998), describe ambient technologies as those that leverage our background processing capabilities, by persistently providing information to users at the periphery of their attention through subtle cues of sound light or motion. In this way students and teachers alike can be made aware of any changes to the state of the information without it requiring their constant attention. The Lantern project (Alavi, Dillenbourg & Kaplan, 2009) used specially designed “lanterns” (small LED lit towers) to help teaching assistants (TAs) know which student groups needed assistance during first-year undergrad Calculus recitation
sessions. When students had difficulty in solving a problem rather than holding up their hand and waiting for the TA to come over to them (often meaning that the students would stop working and focus on getting the TA’s attention), they would turn on their lantern to let the TA know they needed assistance. The students could set the lanterns to specific colors for each problem, and the longer they waited for the TA the faster the lights would blink on and off. With this technology, the TA was able to see at a glance what question each group was on and how long each had been waiting for assistance. The students, knowing that the TA was aware they needed help, could go back to working on the problem in hopes of solving it without assistance. Results of this study showed that the ambient representation increased fairness (students being helped in order), student time on task, and the number of students who solved the problem for themselves while waiting for assistance. The ability of lantern to move seamlessly between the center and periphery of attention (Weiser & Brown, 1996), without disrupting the flow of other class activities, highlights the potential for ambient technologies in helping regulate and support the orchestrational load of participants.

2.5.4 Orchestrable technologies.

Orchestrable technologies are those technologies whose precise function can be determined or adapted both before and during an activity. In some cases, these technologies add a layer of flexibility to the script by allowing for fine-tuning and real-time adaptation of the script (by either the teacher, the students, or the system itself). In EvoRoom (Lui & Slotta, 2013), the teacher has their own “orchestration tablet” that allows the teacher to change the time period of the simulation across millions of years, depending on the kinds of habitat and ecology she wanted the students to investigate. Other orchestrable technologies are those that Tchounikine
(2013) calls affordance creating technologies – technologies whose usage is likely to produce “pedagogically rich events”. These technologies are included as part of the script, however they are not prescribed to a single method of use. Instead they are left somewhat unbounded (similar to Dillenbourg’s notion of light coercion), giving the teacher (or students) a higher degree of freedom in how they will use it. In Wallcology, the use of the aggregated representations of student lifecycle observations were not hard-coded into the script, rather their use was left unbound, and both teachers and students were free to reference them at any time during the activity’s enactment (Cober, McCann, Moher & Slotta, 2013). Examinations of the use of the aggregates showed that the teacher was able to dynamically adapt their use for classroom discussion based on the emergent ideas (and misconceptions) of the class.

2.6 Intelligent Agents for Orchestration Support

One set of technologies that can be a powerful facilitator, both as an orchestration technology and as an orchestrable technology, is that of “intelligent software agents” – small, active software elements that can respond to current contexts, or past actions of participants, performing real-time data mining operations, and operating on semantic metadata (Brusilovsky, 2001). In addition to their use in education (Serenko & Detlor, 2002; Yau, Gupta, Karim et al., 2003), intelligent software agents have seen significant growth in recent years across multiple sectors including business and e-commerce (Papazoglou, 2001; Jennings, 2001), health (Abowd & Mynatt, 2004; Cook & Das, 2007), air traffic control (Wooldridge & Jennings, 1995), and video games (Stanley, Bryant & Miikkulainen, 2005). What separates agents from traditional software is that agents are capable of responding to the state of their environment and conducting flexible autonomous actions in order to meet their design objectives (Jennings & Wooldridge,
Building upon Jennings and Wooldridge’s work, O’Driscoll, Mithileash, Mtenzi & Wu
(2008) state that for educational settings, agents need to be particularly aware of the context in
which the learning takes place, the identities of nearby people and objects, the social setting
(individual, small group, or whole class settings), the specific activity being performed, and be
able to adapt according to its location (both physically and digitally) or any changes that might
happen to these factors over time. O’Driscoll et al. (2008) implemented a Context Aware Smart
Classroom (CASC) in which instructors and students in an undergraduate Electronic and
Engineering program were given Bluetooth tags which connected them to a timetable and a
course management system (CMS). When a teacher entered a CASC enabled classroom, the
system (using Bluetooth sensors) would recognize the instructor’s presence, cross-reference him
or her with their timetable (recognizing what class the instructor was scheduled to teach), and
turn on the lectern and bring up the instructor’s lecture slides. CASC would also recognize all the
students within the room and send the lecture slides and any required materials from the CMS to
their registered devices (smartphones, laptops, or tablets). This example shows how agents can
respond to a single event (e.g., a single lecture), however there is a growing interest in how
agents can leverage persistent curricula.

There is also the potential for agents to analyze individual and whole class learning traces and
evolving metadata tagged learner-generated artifacts (Roschelle, Dimitriadis & Hoppe, 2013)
across multiple scales of time and learning spaces. The assignment of students to groups, and the
assignment of materials to groups can be informed dynamically by processing the metadata of
what materials students have worked on previously, or what locations in the room they have
previously visited (Tissenbaum & Slotta, 2013). Intelligent agents hold particular promise for the
design of scaffolding environments to support inquiry learning, in part because they allow orchestration of scripts that are deliberately *ill determined* at the outset of orchestration (i.e., scripts where it is not known, *a priori*, what outcomes or conditions will emerge from the products of student interactions). The use of intelligent agents allows for open-ended designs, enabling the script to evolve in relation to student interactions. Slotta, Tissenbaum & Lui (2013) identify three important pedagogical roles that can be played by intelligent agents in the scripting and orchestration of an inquiry curriculum:

1. **Content Agents**

   This refers to the use of intelligent agents for managing, building and retrieving content. What is the current domain of a student’s inquiry, and what learning context, group or tool are they learning with? By understanding the content that students are, or have been, working on, intelligent agents can update students on changes to that content or connect it to other artifacts for knowledge work. Agents also have the opportunity to inject materials into the script, e.g., by populating a student’s “drawer” (within a particular learning environment) with all content materials that are tagged by students – even those appearing in real time.

2. **Activity Sequencing Agents**

   As student- and system-generated semantic metadata emerge, data-mining agents can connect users with materials, as described above, but can also make assignments to learning activities or conditions. Sequencing agents can process a student’s interactions, while also monitoring global (i.e., community level) metadata, to determine the next activity, tool, or location for the student. In this way, the script does not have to be identical for all students, and can be seen more as a
map of activities, that students can traverse in many pathways. Sequencing agents help determine what parts of the map may be accessible, in accordance with emergent metadata and scripting logic.

3. Grouping Agents

The ability to know the history of student interactions, both individually and as part of the larger community, allows for the design of intelligent agents that can dynamically group or sort students according to specific pedagogical logic. This has particular significance in reducing the orchestrational load for teachers, by helping track and manage which students have worked with whom, what materials students have covered in past activities, or any groups (e.g., tasks or expertise groups) to which they have previously been assigned. Intelligent agents can group students with peers according to metadata that is emerging in real time—an activity that would be practically impossible for any human to perform.

2.7 Distributed Technology Enhanced Learning (DTEL) Environments

Over the last two decades, multiple researchers have investigated the role that Technology Enhanced Learning Environments (TELEs) can play in supporting students in the acquisition of skills and knowledge (Wang & Hannafin, 2005; Dreyer & Nel, 2003; Hannafin & Land, 1997). Within knowledge communities in particular, there has been a growing desire to understand the how this knowledge is distributed within and across the community (Dede, 1996). Salomon, Perkins & Globerson (1991), argue that distributing the information processing load between the technology and the students, can free students to focus instead on constructing new knowledge, allowing for more “intelligent” performance than could be performed by humans alone. These
technologies can also play an important role supporting the knowledge community by representing dynamic concepts, complex representations, and establishing co-reference among community members (Pea, 1994).

In such environments, the community’s collective intelligence does not need to be encompassed within the “skulls” of any one individual member, rather it can be distributed amongst the community members, and the tools they use to contribute to the community and collaborate with each other (Hollan, Hutchins & Kirsh, 2000). Hewitt & Scardamalia (1998), point out that this distribution of cognition, does not mean “divided up,” like pieces of a cake; rather, it is “spread over,” like weather systems in a geographical area, where each element is continually affecting the others in the system. Pea (2004), terms this “spreading” of knowledge across the various tools, spaces (both physical and digital), scales of time, and participants as Distributed Intelligence (DI). A central characteristic that distinguishes DI from other technology-supported models of learning, is the explicit notion that the scaffolds cannot be “faded” away, rather they are intrinsically part of the community’s learning and intelligence, and any attempt to “remove” the scaffolds would be subsequently remove a vital part of the community (Pea, 2004).

There is a growing need to consider these two models, Technology Enhanced Learning Environments and Distributed Intelligence, not as mutually exclusive approaches to learning and curricular design, but as synergistic approaches that support students working as a knowledge community. To this end, we suggest a model in which the technological, social, spatial, and temporal elements are considered collectively in support of students as a knowledge community, which we term Distributed Technology Enhanced Learning (DTEL). Below, I describe five central elements in the design and development of DTEL environments: (1) smart classrooms;
(2) mobile, collaborative, and interactive technologies; (3) spatial, embodied, and tangible interactions; (3) user-contributed content; and (4) support for seamless and cross context learning.

2.7.1 Smart Classrooms.

Despite any progress in our scientific understandings of learning, and the significant advancements in educational technologies, the majority of today’s classrooms remain quite similar to their form and function across the previous century (diSessa, 2000; Makitalo-Siegl, Zottman, Kaplan & Fischer, 2010). Certainly, the physical environment of the classroom has remained unaffected by science or technology, which would clearly implicate the nature of learning and instruction that it could support. If our aim is to engage students in authentic collaborative and inquiry-based practices, it follows that we should not think of the physical environment as a neutral setting. The ways in which we design these learning spaces and the ways in which students interact with the information within these spaces can lead to completely different forms of orchestration, collaboration, and patterns of learning. Just as Scardamalia and Bereiter (2006) argue that technologies need to be specially designed in order to support specific pedagogical designs, so to must the spaces in which the learning takes place.

Many researchers are now advocating for the notion of “smart classrooms,” in which the walls, floor, ceiling, and furniture all become mediators of students inquiry, such that students’ locations within the environment could mediate who they collaborate with or what materials they work on. These are spaces in which users are not just passively browsing information, but are also creating, attaching, connecting or taking data with them from one location to another, or from one group to the next, and where intelligent agents and real time data mining techniques
help track and respond to emergent patterns in the class (Slotta, 2010; Rekimoto et al., 1998; Martinez Maldonado, et al., 2012; Zufferey et al, 2009; Simon et al, 2003). This integration of CSCL environments into real classroom setting is what Dillenbourg at al. (2011) call the Third Circle of Usability, and is an essential component for supporting complex orchestration.

2.7.2 Mobile, Collaborative, and Interactive Technologies.

The growth of high-speed WiFi networks in schools and the dropping price of digital hardware (smartphones, tablets), has introduced new opportunities for mobile and pervasive computing technologies, unchained from traditional computer lab settings. This shift has made such devices particularly compelling for K-12 education, as it allows a transition from the occasional or supplemental use of computing technologies (i.e., when students visit a computer lab), to more frequent and integral use in their everyday class activities (Roschelle & Pea, 2002). Roschelle and Pea (2002), further argue that a movement to a 1:1 ratio of personal computing devices is the first step in realizing the potential of computational technologies to transform learning. Providing students with devices at a 1:1 ratio also allows them to receive customized, personalized, and context relevant content. This content may be “beamed” by the teacher directly to the student or by an intelligent agent running on a background server that is tracking the student’s progress and place within the script. The increased portability of tablet computers and smart phones means that students are not locked into traditional rows of classroom seating, but are rather free to move around the room, forming either ad hoc or scripted groups. The disruption of the traditional classroom setup also frees the teacher from being either the “sage on the stage” or the “guide on the side”, to rather serve as a “conductor” of the class performance, moving among groups and aiding students as needs arise (Pea & Maldonado, 2006).
Although the size of handheld devices is useful for individual interactions, problems arise where a script entails that students engage in group collaborations or whole class discussion (Liu & Kao, 2007). In response, many designs couple the smaller handheld devices with larger, sometimes interactive displays, which can be used to aggregate individual student work to promote small group or whole class discussion. Crouch and Mazur (2001) used a large display at the front of the class to aggregate individual student responses to multiple choice problems as a way to engage the whole class in discussions around commonly held misconceptions in the domain of physics. Similarly, Cober et al. (2012) aggregated individual student observations of predator prey relationships in an embedded phenomenon simulation (made on tablet computers) on a larger interactive whiteboard at the front of the class as a means for engaging the class in discussion on differences in opinion and to build consensus.

The placement of student work on large displays can also help facilitate small group discussions, whereas smaller displays tend to force students to fight for control and view of the screen (Liu & Kao, 2007), and may result in pushing some students to the periphery and out of the collaborative process (Tissenbaum & Slotta, 2012). In the UniPad *Housemates* project (Kreitmayer et al, 2013), students of finance were tasked with budgeting their limited disposable income in a shared house setting. On their personal tablets, students chose how to spend their individual funds, while the whole house’s (their group’s) expenditures were shown on a shared aggregate display, in real-time. This shared aggregate was used as the basis for group negotiation on how to best make individual expenditures fair for everyone in the house. Results of the study showed high collaboration and discourse among group members and high levels of engagement.
Placing the aggregated products of individual or collaboratively constructed work on a large format display can also be a powerful tool for supporting teacher orchestration. Just as an individual device’s small screen makes it difficult for students to collaborate, it can also make it difficult for a teacher to see what students are doing, forcing him to guess what work (if any) students are doing and where he or she is most needed. Sharples (2013), notes that in the BeGUILE project teachers often struggled with knowing where to be in the classroom and which students to attend to because they could not see through the lids of the student laptops. In contrast, placing group physics problem solving on large format displays has been shown to help the teacher in deciding where to go in the room (Tissenbaum, Lui Slotta, 2010).

Clearly, it is not enough to simply instrument a learning environment to ensure that learning will occur. Rather, the design and implementation of educational technologies needs to take into consideration the specific learning and educational approaches those technologies afford (Kirschner et al, 2004). Unlike some scaffolded environments, within DTEL environments, these technologies are a persistent and pervasive part of the learning ecology. Pea (2004) argues that such technologies are part of the “distributed intelligence” of the class, and their mediation between students, scripts, raw data, and the collective knowledge is intrinsic to the class’ learning. Hewitt & Scardamalia (1998) support this notion, arguing that learning tools that are carefully designed in support of specific pedagogical goals become cultural artifacts that carry aspects of collective intelligence. Over time, these digital objects can record traces of their use, becoming imbued with a social imprint of student collaboration and interaction (Hollan, Hutchens & Kirsh, 2000) to render them as important artifacts within the class’ collective epistemic history.
2.7.3 Spatial, Embodied, and Tangible Supports for Inquiry.

Instrumenting classrooms with rich and interactive technologies (e.g., tablets, interactive whiteboard and tabletops, and RFID sensors) can radically affect the ways in which we experience these spaces and our sense of presence both as individuals and in groups (Ciolfi, 2004). As the room’s physical dimensions become a mediator of class interactions we can begin to experiment with new ways to support individual, small group and whole class knowledge construction. Instead of directly sending messages to particular students, information can be embedded within a specific physical context, allowing students to indirectly communicate by “leaving” information for others to receive when they enter the space (Rekimoto et al., 1998). By leveraging space as a filter for a community’s knowledge we can also reduce information overload by only providing information that is contextually and spatially relevant (Oh & Woo, 2009). By combining spatial awareness, including who else is co-occupying a space, and their respective places in the script, we can further control the distribution of materials and the formation of ad hoc collaborations.

Within the design of smart spaces, we can recognize the need to understand an informational “second space” which is layered on top of, within, and between the fabric of traditional physical space (Graham, 1998). The goal then in designing these environments, is to leverage their spatial affordances towards making this second space explicit and meaningful for users. McCarthy et al. (2004) use RFIDs embedded in conference badges to display the names and interests of nearby attendees on large-format displays as a way of promoting conversations. In RoomQuake (Moher et al., 2005), seismic activity is simulated as being mapped to the spatial confines of the classroom. Students must use a combination of handheld computers (placed at specific locations
around the room), measuring tapes, and Styrofoam balls to triangulate the epicenter of quakes, in order to figure out the where a fault line runs across the classroom. In RoomQuake, the physical layout of the room is a major driver of the inquiry processes, as a group’s location in the room directly determined the information provided on their Palm Pilot, and requires them to work with the other spatially distributed groups in order to solve the task.

Recent advances in touch surface technologies, including Android smartphones and tablets, Microsoft’s multi-touch surface computing, and interactive whiteboards has brought new forms of sensing and manipulating our environments (Ishii, 2007). With the introduction of interactive “wands”, like the Nintendo Wiimote, users can control and manipulate images and events on large screens or projected walls by pulling, turning, flicking or clicking (touching) them. Similarly, with the Microsoft Kinect, users can now directly interact with computer-projected images, and more generally with their 3-dimensional surroundings, using computer vision that tracks users as they move within the space, wave their arms, or interact with both real and virtual objects. In addition to their intended applications for highly interactive (and active) forms of gaming, such technologies can allow researchers to explore dramatic new forms of learning interactions. Educational researchers can now begin to investigate how learners’ ability to physically interact with the “digital bits” of their community’s knowledge might foster new forms of learning, knowledge construction, and collaboration. As these tangible interactions find their way into educational designs, new challenges arise around the semantic meanings of these interactions, the physical forms they take, and the materials used in their construction (Hornecker, 2011).
Weiser (1994) argues that the design of these physical computing interfaces should make the coupling of the digital and physical “invisible”, enabling the computer to disappear into its physical and social surroundings. This coupling of the physical and the digital offers new opportunities for learners to embody their complex relationships with these objects and their underlying information within dynamic and evolving social contexts (Dourish, 2001). Combined with the physicality of the space and student movement within the space, these environments offer the opportunity to promote kinesthetic forms of learning within a rich sensory spatial context (Dunleavy, Dede & Mitchell, 2009; Lyons, Slattery, Jiminez, et al., 2012). Projects such as SMALLab (Birchfield & Johnson-Glenberg, 2010) and A Mile in My Paws (Lyons et al., 2012), created physical and embodied interactive environments where students engaged with personally relevant and interesting topics such as climate change, ancient civilizations, and even cooking.

The research domains of embodied and immersive interactions can be further extended through the use of Augmented Reality (AR) in which the real physical environment (e.g., at a museum, or on the street) is enhanced with additional layers of digital information (Dalgarno & Lee, 2010). In educational settings, augmented, immersive and embodied learning environments have taken on many different forms, such as simulated ecologies of bugs living in classroom walls in Wallgology (Moher, 2006), the evolution of rainforest fauna and flora over millions of years in EvoRoom (Lui & Slotta, 2013), a forest augmented with sensors, speakers, and visuals displays in Ambient Wood (Price & Rogers, 2004), and an alien invasion in Alien Contact (Dunleavy, Dede, & Mitchell, 2009). Dede (2005) offers several ways in which these approaches enhance students learning styles including: developing fluency in multiple media; promoting collective
rather than individual seeking, sieving, and synthesizing experiences; promotion of active learning based on experiences (both real and simulated) that include frequent opportunities for reflection; the ability for expression through non-linear, associational webs of representation rather than linear stories; and the co-design of learning experiences personalized to individual needs and preferences.

Although these approaches hold significant promise for promoting new forms of student learning, engagement, and inquiry, there are still several challenges in their implementation: once an interesting application is designed, it is not trivial to support students and teachers to enact the activities and materials. In their work on AR with the Alien Contact project, Dunleavy, Dede, and Mitchell (2009) note that both teachers and students suffered from high levels of cognitive load, with the teachers stating that the overall curriculum was “overwhelming” for them. Similarly in Wallgology, Moher (2006) notes that teachers often struggled to manage the complex flow of students and materials that were required during the enactment of the curricula. These challenges further illustrate the need for the development of supporting technology infrastructures to help manage some of the orchestrational load.

### 2.7.4 User-Contributed Content.

Having grown up in the “Web 2.0” landscape, outside of school, students are increasingly the curators, creators, commenters, and classifiers of the products and networks with which they interact (Dohn, 2009). Such user contributed content (UCC - Vickery & Wunsch-Vincent, 2007) can take on many different forms, from collections of user-contributed artifacts (e.g., Flickr, YouTube), to community generated social spaces (e.g., Facebook, Academia.edu), collaboratively generated and edited evolving content (Wikipedia), and newsfeeds or other
socially filtered resource streams (e.g., Reddit). Even games and leisure spaces are now deeply infused with asocial component (e.g., World of Warcraft, Fantasy Sports).

There has been some evidence showing that UCC can promote deeper engagement with the content and the community, because users can see themselves as active participants in the community’s progress (Tedjamulia et al., 2005) and because of the awareness of their being an “audience” to see, critique, and build on their own contributions (Wheeler, Yeomans & Wheeler, 2008). The content in these communities is not static nor is it siloed, rather participants can experiment by building new artifacts by combining services and information, or “mashing up” and “remixing” multiple data streams (such as sound, text, and video) for their own needs (Franklin & van Harmelen, 2007). This architecture of participation (O’Reilly, 2004), finds an ideal home in knowledge communities approaches to education, while simultaneously offering unique opportunities and challenges for the orchestration of smart classroom activities.

The use of user-contributed content introduces a level of variability to the evolution of the community knowledge base, as the kinds of materials submitted, the questions asked, and the assignment of metadata and tags are (although supported by scripts and scaffolds) ultimately up to the students to generate. To the extent that any scripted activities depend on student-contributed materials, it is not actually possible to know in advance the complete content or structure of such activities. Metadata, such as student-generated tags or votes, may emerge as a result of the enactment, and activity sequences may be scripted such that they depend on those emergent features. The need for scripting decisions to be made based on this emergent and variable data further support the need for well-designed agents to help facilitate their orchestration.
2.7.5 Seamless and Cross-Context Learning.

As inquiry investigations become more complex, they increasingly extend beyond traditional classroom walls, and across a multiplicity of formal and informal spaces. Powered by the advancement of mobile technologies we are increasingly seeing curricular designs that take place in the playground (Sollervall, Otero, Milrad et al., 2012), at museums (Kuhn et al., 2012), around university campuses (Kohen-Vacs et al., 2011), or on environmental field trips (Zimmerman & Slotta, 2003). With more than two thirds of young adults now owning a web-enabled smartphone in the United States (Pew, 20121), there is a growing technological capability for students to engage with their learning community “on-the-go.” Social and semantic metadata can play a powerful role in creating a “chain” that connects student learning across these formal and informal learning contexts and across diverse scales of time (rather than in traditional single class periods – Milrad, Wong, Sharples Hwang & Looi, 2013). In conjunction with scaffolding and context aware software (such as agents), the use of metadata can “seamlessly” (Chan et al, 2006) connect students to the larger class community and the collective knowledge base, whenever and wherever they are situated (Wong & Looi, 2011). On their own, such technological affordances are not sufficient to ensure effective learning designs, but they do provide new opportunities for research into such forms of learning. This is especially valuable for the learning science community, as research has typically focused on either formal or informal learning and not the synergistic connections and learning that take place across and between these settings (Looi et al., 2010). A challenge in the design of seamless cross-context learning is in designing the

interfaces by which students engage with the knowledge base and curricular materials in each context. The informational and pedagogical needs of students at home on their own are vastly different than when they engage in groups in a smart classroom setting. Therefore, significant care must be taken to understand the kinds of interactions students are likely to engage in within each context and develop appropriate supporting tools.

2.8 Co-Design of Smart Classroom Curriculum

Even when well designed the implementation of innovative technology enhanced curricula into the authentic everyday practices of teachers is a challenging task. The adoption of such practices is heavily dependent on how well a teacher perceives the “fit” between the intervention and their goals for students, teaching strategies, and expectations for student learning (Roschelle, Penuel & Shechtman, 2006). In order to ensure that these conditions are met to teachers’ satisfaction, there is a growing call to involve them as co-designers of the technologies and curricula from the outset. This co-design approach contrasts other design approaches, in which teachers are simply expected to follow pre-defined scripts in their teaching, instead viewing teachers as active participants and professional contributors (Penuel, Roschelle & Shechtman, 2007). This approach of gaining insight directly from stakeholders during the design process follows in the footsteps of successful design approaches such as user-centered design (Sanders, 1992). However two main features separate the co-design approach from that of user centered design: User-centered design tends to solicit feedback on already enacted designs rather than involving users as initiators in the design process (Scaife et al., 1997); and the focus on single users in user-centered designs fails to take into account the highly connected and interrelated interactions present within complex socially mediated designs (Sanders & Stappers, 2008).
Moving towards a co-design approach requires a shift away from traditional design-as-expert approaches towards realizing that everyone can be creative and productive to the design process. This includes and understanding that teachers’ (and even students’) experiences in the “real-life” of the classroom can provide unique and powerful insight into the effectiveness of curricular designs. Penuel et al. (2007) point out that this approach represents a significant evolution in the social dynamic between researchers and teachers and introduces new tensions to the design process, including time constraints on teachers; the sometimes very different workplace norms between developers and teachers; that a commonly understood language is always a work in progress; and perhaps most critically, at the outset teachers often do not have a strong sense of ownership in the project or their specified role in the design process. Roschelle, Penuel & Shechtman (2006) outline seven characteristics to address these tensions and characterize a successful enactment of the co-design process:

- The co-design process takes on a concrete, innovative challenge
- The process begins by taking stock of the current practices and classroom contexts
- The co-design has a flexible target
- The co-design needs a bootstrapping event or process to catalyze the team’s work
- The Co-design is timed to fit the school cycle
- Strong facilitation with well-defined roles is a hallmark of co-design
- There is a central accountability for the quality of the products of co-design

Despite the higher load placed on the design process, this approach to technology-enhanced curricula has seen continued adoption in the development of learning environments for many domains, including ecology (Spikol et al., 2009; Vogel et al., 2010), physics (Charles et al, 2011)
math (William, 2003; Nilsson, Sollervall & Spikol, 2010), as well as for informal learning spaces such as museums and science centers (Fuks et al, 2012; Stuedahl & Smordal, 2012; Bortolaso, et al., 2012).

This approach to design is particularly vital in the design of DTEL interventions, as their implementation requires a major reconceptualization of classroom practices, interactions between teachers and students, and the role the physical space itself plays. In order to ensure that these innovations are properly understood, implemented, adopted, and more importantly is addressing real classroom needs and challenges the teacher must be brought into the design process as early as possible.

2.9 Design-Based Research

Within the field of learning science research there has been growing push towards addressing theoretical questions about the nature of learning, not within well controlled laboratory settings, but instead in natural real-world contexts and settings (Collins, Joseph, Bielaczy, 2004). This shift to authentic learning settings was first advocated in the seminal work by Ann Brown (1992), where she argued that it was impossible to isolate one aspect of student learning, test it, and stick it back in; rather, one must investigate it within the natural contexts in which it occurs. This is especially true in CSCL learning environments, where the cultures in which innovative technologies and pedagogies are introduced can evolve in ways that cannot be predicted in canned laboratory settings (Hoadley, 2002). This split, between conventional educational research and the problems and issues of everyday practice, requires development of a methodological toolkit that can derive evidence-based claims from these natural learning settings (Barab & Squire, 2004). In response many researchers have advocated the notion of a “design-
based research” approach, which attempts to ground research within these real-world contexts and the multitude of variables present during their enactment (Wang & Hannafin, 2006). It is worth noting that design-based research has fallen under several other names, including design experiments (Cobb et al., 2003). Sandoval and Bell (2004) argue however, that the use of the word “experiments” connotes a specific form of controlled experimentation that does not adequately convey the breadth of the approach; similarly, “design research” is too easily confused with “research design” which lacks the critical in situ components.

Unlike other design approaches, such as user experience design, the major goal of design-based research is not to find applications of technology, but to advance learning (DBRC, 2003). Within the chaotic enactment designs that are situated in real classroom settings, design-based research attempts to reveal which features of a design are essential for learning and which features are irrelevant to our desired learning goals (Hoadley, 2002). In design-based research, the design process is neither linear nor prescriptive, rather interesting forms of learning and new lines of inquiry often occur opportunistically during the design’s enactment, and retrospective analysis may often be required to validate them (Mor & Winters, 2006). This retrospective analysis then becomes the driving force for successive design iterations, fostering continuous cycles of design, enactment, analysis and redesign (DBRC, 2003).

Because of the culturally embodied nature of the interventions and the complexity of real-world situations, design-based research forgoes the commonly held requirement of replicatability (Collins, Joseph & Bielaczyc, 2004; Hoadley, 2002). Some critics of design-based research question the scientific value and lack of “evidence” of designs that cannot be replicated (Mor & Winters, 2006). Hoadley (2004) argues that on the contrary a well executed design-based
research intervention can actually provide a greater level of rigour and “evidence” through its ability to help connect the intervention to specific outcomes, which can lead to better alignment between theory, treatments, and measures in complex realistic setting like the classroom.

Generally, design-based research does not attempt to validate the value of a particular curriculum, rather it strives to advance a particular set of theoretical constructs that transcend the environmental particulars in which they were enacted (Barab & Squire, 2004). Ultimately the design itself and its enactment are seen as being a significant outcome of the research. Along with the documentation of the design and implementation, another goal is to create a rich narrative of the changing understanding among implementers and researchers relating to the impact of the intervention (i.e., how the enactment did or did not embody the hypothesis under investigation - Hoadley, 2004).

The need to maintain a productive collaborative partnership between researchers, implementers, and participants in the research context is well suited to the approaches of the co-design methodology. Dede (2004) goes one step further, stating that in order for design-based research to succeed or have any hope of adoption by practitioners and policy makers, we as researchers must “view them as partners with valuable knowledge for co-design rather than as experimental subjects to manipulate.” As design-based research is naturally cyclical, its coupling with co-design is a natural extension, as it would be nearly impossible to conduct iterative refinements of educational materials without the direct involvement of the teachers or other participants who are implementing the versions.
Chapter 3: Initial Design Studies

Developing an understanding of the orchestration (i.e., of teachers, students, materials, tools and activities) within a distributed technology-enhanced learning (DTEL) environment, and developing the corresponding technology supports cannot be achieved over a single intervention; rather, it takes multiple design cycles in which elements of the curricular and technological supports can be carefully examined and refined based on participant feedback and qualitative and quantitative measure. From the outset we knew that we wanted to develop a substantive curricular intervention, in which students engaged in prolonged and meaningful experiences and knowledge construction as a community. This was motivated by the theoretical space within which the research is situated: that of knowledge communities and the KCI model in particular. However, we first required a set of smaller, targeted studies to inform some basic understandings on how different elements within a DTEL environment might support such a community.

To that end, we began with a series of short, targeted investigations that addressed some of the primitives relating to the spatial distribution of students and tasks, the pedagogical control of activity sequences, the use of aggregate and ambient displays, and the role of the teacher in orchestrating class activities. The process of designing and enacting these learning activities and their respective technology elements led to findings about learning in technology-enhanced environment, the design of collaborative and collective learning activities, and specific advances for our technology that facilitated our development of S3.

3.1 Study 1 – Introducing tagging and solving physics problems, and aggregated visualizations of student contributions
3.1.1 Design Goals.

The first study explored basic approaches to aggregating and representing student-generated content, and also tested some early elements of the technology framework. The activity focused on small groups engaged in physics problem solving, and explored the effectiveness of whole class aggregation in supporting students during this task. We analyzed measures of accuracy (i.e., of student tagging), and the frequency of groups correctly solving their assigned problems. We also looked at how effective the aggregation of student work was in supporting the teacher’s orchestrational decision making.

3.1.2 Method.

Two grade 12 Physics classes (n=32) took part in the intervention, which was conducted over two days with two different instructional conditions (one on each day) and sixteen students in each condition. In each condition, students were organized into four groups (with each group assigned to one “zone” in the room), where they worked individually to Tag, Answer, and provide Rationales (TAR) for a set of sixteen multiple-choice, qualitative physics problems (Lui, Tissenbaum & Slotta, 2011). Once this “individual” stage was completed, students worked as a group, provided with four of the sixteen questions, as well as the aggregated TARs from all 16 individuals. Each group was then asked to form a consensus on a “final answer” for each of their four problems. Finally, each student group was presented with four new “long-answer” (quantitative) physics problems. For each of these long-answer problems, the group was asked to select, from their earlier discussed qualitative problems, which ones was most related to the current problem. The group was then tasked with choosing a set of elements and equations that would help set up the problem for solving, and provide rationales for their choices of formulas.
For the second intervention, we introduced a condition wherein the work of two of the groups was broadcast on large-format shared displays in the smart classroom, whereas (similar to day one) the other two groups only used their laptops for collaboration.

### 3.1.3 Data Sources.

Data were drawn from four sources: (1) All problem responses, tags, and rationales were captured by the system; (2) Video recordings of the curriculum activity; (3) Researcher field notes; and (4) A follow-up debriefing with the co-design teacher. The combination of the field notes and recorded video provided us with insight into how the smart classroom facilitated curricular enactment, student collaboration, and teacher orchestration. The follow-up debriefing with our co-design teacher gave us an understanding of the match between the intervention (and the supporting S3 technology) and the teacher’s curricular goals, as well as insight into orchestral issues. The captured student data (retrieved from server data logs) was analyzed to determine changes in accuracy between individual and group responses (including accuracy of element tags), and any differences between the two conditions. Student responses and tagging were compared with an “expert model”, where each problem was tagged and solved by the classroom teacher.

### 3.1.4 Findings.

Compared to working individually, the student groups tagged (with concepts and equations) their problems closer to the expert model (Figure 2). Average accuracy scores were 80.94% (groups) compared to 76.57% (individuals), which was not significant, although it should be noted that this was a small-n study. A second finding focused on the condition where half the groups in day
two were shown on large-format displays in addition to their laptops. Although increased group versus individual performance was again found in both conditions, the shared display groups showed higher gains in their correct answers (from 53.13% to 87.50%) as compared with the groups who used only laptops (from 58.33% to 59.72%) (Figure 3 - Tissenbaum, Lui & Slotta 2012). One possible explanation is that the large-format displays allowed the teacher to see what students were writing in their summary responses as they were typing, allowing “real-time” feedback. For example, in one episode, the teacher was watching a group discuss the TAR responses from the individual session, and noticed that no students from the individual phase had actually approached the problem correctly. In other words, the aggregate data was flawed. In this case, the teacher was able to respond, advising students that, in this case, it may be better “not to listen to the wisdom of the crowd” (Tissenbaum, Lui & Slotta, 2011). Additionally, video analysis indicated that the large format displays were effective as a common reference for orienting student discussion and collaboration and for providing indicators of class progress (Lui, Tissenbaum & Slotta, 2011).

![Figure 2: Individual vs. Group Accuracy in tagging physics problems](image1.png)

![Figure 3: Group versus individual performance on laptops and shared displays](image2.png)
3.1.5 Discussion.

The aggregation of individual student work appeared to help the groups in improving their understanding. This may have been due in part to the challenge of reconciling their tags, and leading to concerted reflection about the problems. The large format displays also appeared to provide some advantage over the small, shared displays (ie, a group laptop) in facilitating collaboration. Part of the reason for this may have been the ability of the screen to provide a common referent for groups. The large display also provided additional real-time information on student work to the teacher, enabling him to make better-informed orchestrational decisions. From a technical perspective, the technology environment was able to support students in working collaboratively with peers, retrieve and aggregate relevant materials from the database in real-time, and (in the case of the large format displays) spatially orient student work within the classroom.

3.2 Study 2 – Adding cross-context learning, and teacher orchestration tools

3.2.1 Design Goals.

Building on the findings of the first design study, that the aggregate views of student work was useful for both the students and teacher, this study responded to the concerns of the teacher concerning how much class time the individual tagging and reflections had consumed. We adapted the curriculum to have the individual students “TAR” the multiple-choice problems as an asynchronous homework activity. This change allowed the teacher to allocate more time to the group activity, and to review individual student work beforehand, which offered him new
opportunities for adjusting the class script based on his perception of student understanding. It also allowed us to begin investigating the important dimension of learning across contexts (i.e., blending home and school activities). To support the cross-context learning, we developed a Web portal (Figure 4), through which the teacher could customize the number and type of questions served to students and see a report on student responses. The teacher also could use the portal during the live activity, to examine the groups’ work in real-time, and to further support class orchestration decisions. For this iteration, we compared two conditions - one where a class completed the group activity in their regular classroom, working in dyads, and another where they collaborated as before, in the smart classroom.

3.2.2 Method.

We engaged two new physics classes, with \( n=20 \) and \( n=16 \) respectively, and the same group of researchers, technologists, and co-design teacher.

![Figure 4: Teacher Portal](image)
Prior to students doing the at-home portion of the activity, the teacher logged into the portal and uploaded the homework questions. Students were alerted via email that the activity had been posted, and were given two days to log into the student site and complete the individual TAR activity. Before the classroom session, the teacher logged into the portal and reviewed the aggregated student work to get a sense of students’ ideas (i.e., from the individual rationales and tags). During the in-class activity, the students repeated the TAR step (i.e., “re-TAR”) from the first iteration working in dyads. During the activity, the teacher was free to use the aggregated visualizations as a source of information about emergent student ideas.

3.2.3 Data Sources.

Data collection for this run was similar to that of the first: All student and dyad tags, answers, and rationales were captured by the system; Researchers collected field notes of the in-class activity; and a follow-up debriefing of the activity was conducted with the teacher. No video was recorded of the in-class or smart classroom activities. The in-class field notes provided us with an understanding of how the students engaged with the curriculum and their peers while in class. The student-contributed TAR responses provided a data source that served to reveal changes in the accuracy of responses and rationales between students answering individually versus in dyads. Finally, the follow-up debrief with the teacher provided insight into his perceived effectiveness of the added technology scaffolds in meeting their curricular goals.
3.2.4 Findings.

Overall the dyads faired significantly better (97% overall accuracy) than individuals working at home (80% overall accuracy) at solving problems, with $t=2.02$, $df=41$, and $p<0.05$ (Tissenbaum,
Lui & Slotta, 2012). These results are confounded by the fact that the dyads were solving the same problems they had seen in homework the night before, but the addition of the aggregated rationales made it worthwhile and meaningful to have students re-engage with the problems.

Throughout the activity, dyads were observed reading and discussing the tags and rationales of their peers, in an attempt to make sense of any differences (Figure 5). In comparing individual rationales versus those constructed in dyads, it was found that in twenty-four (of sixty-one) cases, the dyads’ rationales were unique, indicating that the students did not simply regurgitate the ideas of their peers from the individual answering stage. Although it is possible they simply ignored those ideas, which would be problematic in its own way (Tissenbaum, Lui & Slotta, 2012). Of the remaining 37 answers, 20 had rationales that were considered to be identical, or nearly identical to one of the individual rationales, however it was unclear if this was due to simply regurgitating their peer’s ideas, or if they really believed that the individual’s answer was best. The remaining 17 answers were submitted without any rationale, and were concentrated primarily around 3 dyads (15 of the 17).

During the post-interview, the teacher noted that he found the student reports (provided in the portal) to be helpful in understanding where students were having problems with the content prior to conducting the class. During the first in-class session, although he referred to the real-time reporting, the teacher decided to let the lesson run without adjusting the script, preferring to see how the dyads performed on their own. However, seeing a group struggle on one particular problem forced him to intervene (i.e., adapting his “script”). As a result, the teacher adapted the flow of the activity during the second session, adding more interactions with student groups.
Although the teacher was able to see reports of student activities, he was required to refresh the page in order for it to update, making it difficult for him to know what was happening “in real time”. This was compounded during the second session (held in the regular classroom), due to the fact that the teacher didn’t have the large-format displays to see student work at a glance. Although he was able to walk from table to table, the more restricted access to information about each dyad made his decisions about where to go less informed.

3.2.5 Discussion.

This study reinforced our belief that access to the aggregated work of their peers’ can help students develop more accurate understandings of physics problems. The teacher also acknowledged that access to the aggregated student data helped inform his own thinking, both before and during class activities. However, the fact that the teacher was required to refresh his display during the in-class activity limited its effectiveness as a real-time tool. This was a particularly critical moment in the design of S3, as it showed for the first time a clear need to allow some of the devices in the room to be automatically updated in response to the actions happening in the classroom. It also showed the importance of large format displays as a source of information at-a-glance for the teacher, helping guide his decisions about which group to visit. Finally, we gained insight the ability of DTEL environments to support cross-context learning designs, and to blend synchronous and asynchronous curricular elements.
3.3 Study 3 – Adding pedagogical and technological supports: student expertise areas, a real-time teacher orchestration tablet, and intelligent software agents

3.3.1 Design goals.

Once again, the topic of study was a collaborative physics problem solving, tagging and reflection activity, which informed our studies of collective inquiry, as well as the required forms of technological and pedagogical infrastructure. Our aim was to further enhance the teacher’s orchestral capacity and to further understand how students could use the aggregated work of their peers to inform their own reasoning about physics. We also introduced the notion of an intelligent software agent that could help orchestrate class activities by distributing problems to student groups, which lay the foundation for our S3 agent framework.

The period between Study 2 and Study 3 saw the introduction of Apple’s iPad and Google’s Android tablet computers, which radically changed our notions of a personal computing device in the classroom. These tablet computers added a level of portability, high level computing, and tactile interfaces that far surpassed previous technologies (e.g., laptops and iPod Touches). For this intervention, we decided to focus on developing a tablet application for the teacher, as he was the one moving the most in the smart classroom. The teacher application used a colour-coded matrix (groups-by-problems) to show how each student group performed on its problems in real-time (i.e., green if the group had answered correctly, red if they had answered incorrectly – See Figure 6 below). Pressing any of the coloured squares on the tablet would bring up the group’s TAR, giving the teacher insight into how that group had approached their solution. The teacher could also use this screen to engage a student group in discussion (i.e., if he noticed something interesting or erroneous in their response) or to engage the whole class in discussion if
he noticed patterns (e.g., many red squares for a particular problem or topic). We were particularly interested in how this tablet could provide the teacher with new opportunities for understanding the state of student knowledge in real-time, and how it might affect his classroom orchestration.

In this iteration, we varied a condition whereby only one of the two class sections received the aggregated responses of their peers (although both sections completed the individual homework activity). This allowed us to compare how student groups performed with versus without access to the aggregated responses of their peers.

Figure 6: Real-Time Teacher Orchestration Tablet Application
3.3.2 Method.

Two new grade 12 physics classes were once again used for this study (n=15, n=18 respectively), and the same group of researchers, technologists, and co-design teacher (the same teacher as previous studies).

As in the previous studies, the teacher began by uploading homework questions – in this case, there were thirty-five problems representing five distinct topic areas (seven per topic). Each student was assigned to one topic area, receiving five out of the seven problems for homework. During the smart classroom activity, students were placed in groups of five (one student from each area), and given five questions – one from each area – with special care taken to assure that no member had seen before as homework (i.e., we picked one of the two problems the student had NOT seen as homework). Tracking each student’s prior exposure to items in the knowledge base, in order to ensure that their group received only new problems, was a particularly vexing orchestrational challenge, and one that we felt was well suited to the use of intelligent agents. To this end we developed our first version of an S3 Bucket Agent, which tracked which group each student was in, and all the items the group had been previously exposed to, in order to make a real-time decision concerning which unique problems to serve to the group (Tissenbaum & Slotta, 2012).

During the section 1 of the activity, the student groups were not provided their peers’ aggregated responses from the homework; rather they relied solely on negotiation within their group to solve their assigned problems. During section 2, groups were provided with the aggregated TAR responses from both classes’ individual homework activities.
The teacher was also given slightly different conditions during each section of the intervention: in section 1, the teacher had only the large-format display that showed each group’s real-time work; in section 2, the teacher was provided with the orchestration tablet, which showed the matrix of student responses and allowed him to query past group answers.

### 3.3.3 Data Sources and Analytic approach.

Data collection for this iteration was similar to that of the previous two: 1) All student and group tags, answers, and rationales (TAR) were captured by the system; 2) Researchers collected field notes of the in-class activity; 3) Student and teacher interactions within the classroom were captured on video; 4) A post-activity discussion was held with the participants after the second day’s run to gauge students’ feelings about the intervention; 5) A follow-up debriefing of the activity was conducted with the teacher. Student TAR data was examined to determine any changes in the correct responses between students’ individual responses, compared to the groups’ work without the aggregated work of their peers (Section 1) and in groups with the aggregated work of their peers (Section 2). Finally, the follow-up interview with the teacher gave us insight into the effectiveness of the different tools, towards future refinements.

### 3.3.4 Findings.

In order to evaluate the depth of student understanding in their rationales, working with the co-design teacher, we developed a four-point rating scale. Two researchers evaluated all individual and group rationales using the developed scale (91% intercoder agreement). The group on Section 2 that had access to the aggregated response of their peers significantly outscored both individuals during the homework activity ($t=4.13, p<0.01, df=51$), and the groups from Section 1
that did not have access to the aggregated responses \(t=4.19, p<0.01, df=50\) (See Figure 7 – Tissenbaum & Slotta, 2012).

![Average Accuracy Score](image)

*Figure 7: Students in section two, who had access to all TAR data, achieved a higher average accuracy score (2.0), than students during section one, who didn’t have access to the aggregated data (1.21), and students working individually at home (1.32)*

As in prior designs, the teacher was observed actively moving throughout the class, interacting with students where he felt appropriate. At several points in the activity, the access to ideas being written by the individual groups, available at-a-glance on the large-format displays, prompted him to engage with the students to help them refine their thinking and focus more directly on the physics principles (i.e., rather than just the formulas). The ability of the teacher to be aware of such emergent class patterns (i.e., of focusing on equations rather than the principles), prompted him to spontaneously adopt the mantra of “words more than numbers”.

The teacher’s interactions with the orchestration tablet during this final design were surprising. At first, the teacher was very engaged with the tablet, clicking on and reading different group
responses to see where they may have made mistakes. However, after a few minutes he
abandoned the tablet, stating he found that it was actually distracting him from the more “real
life” flow of activities within the smart classroom. During the activity, he complained that he felt
he was “missing things” when he was looking down at the tablet (i.e., rather than looking up at
the large-format displays, or talking directly with the groups). During the post-interview, he
noted that while it was useful to see where groups had made mistakes on the tablet, because the
students had already completed the task, there was very little he could do at that point (as the
group had already moved on to their next task). Thus, reliance on the tablet was actually
inhibiting his ability to intervene at a moment he deemed to be important. The teacher did praise
several elements of the tablet, but found it more useful as a reflective device, similar to the
aggregated reports provided in the second design study.

Similar to previous studies, we found that the configuration of groups around the large-format
displays had a noticeable impact on groups’ internal interactions. Overall, the large displays
allowed even the group members most distal from the controlling laptop to still view the screen
and engage in productive discourse with their peers.

Another important outcome of this study was that the S3 agents were able to successfully
distribute materials to groups based on the requirement that none of the individual students has
previously encountered them during the homework activity. This success of the intelligent agents
to enact a pedagogical condition was notable, given that the task was somewhat unbound (i.e.,
having to distribute problems based on conditions that were defined \textit{a priori}, but for which
outcomes were not), and was taken as an encouraging foundation for more complex pedagogical
conditions in the future.
During the post-activity discussion, students commented that although they found the insight from their peers to be useful in understanding different approaches to solving the problems, having the aggregated multiple-choice answers (presented as a bar graph) made choosing the right answer too easy. This may have been particularly evident given that there were no cases where “the wisdom of the crowds” had generated a wrong answer.

### 3.3.5 Discussion.

This final design study supported our previous findings that the aggregation of student ideas can be used as an important scaffold for follow-up student activities. This design also provided more insight into the role that large-format displays can play – both in supporting small group discussion or negotiations, and as an orchestral tool for the teacher during real-time activities. Our first experience in introducing an orchestral tablet for teachers revealed the importance of thoughtful design - not only of technology and materials, but also of the ways in which we suppose that teachers would use that device within the flow of activities within the classroom (i.e., its role within the “orchestration script”). Our first attempt conflicted with the informational needs of the teacher during the real-time activity. This underscores the need to fully understand the “temporality” of when certain information or interaction patterns are relevant within the script. The initial success of the S3 software agents was also encouraging, in that it lay out the groundwork for more complex interventions in the script and a greater role in reducing the orchestral load of the teacher. Going forward, we would rely on such agents to reduce the need for the teacher to manage such elements of the classroom (especially when those elements are processing intensive), freeing him or her to focus on the critical task of helping students.
3.4 Synthesis of Design Findings

The three studies above informed our understandings of how to support distributed, collaborative, real-time activities within DTEL environments. This section synthesizes those findings into a set of orchestrational, pedagogical, and technological design principles.

*Orchestrational design principles*, are aspects of technology and activity design that pertain to the successful enactment of a desired activity sequence – including teacher supports, use of ambient displays, agent-based assignments of materials or groups, and other strategies or scaffolds. *Pedagogical design principles*, refer to the design of technologies and scripted interactions that can support productive student collaboration and problem solving, including the assignment of individual or group roles. *Technological design principles*, deal with the specific hardware and technology frameworks that support the DTEL environment – including the use of specific devices and displays, and the methods for distributing materials or students in the room, and responding to emergent class patterns. These principles have served to guide our subsequent designs of DTEL activities, and will be used as a lens for discussion in Chapter 6.

**Orchestrational Design Principles:**

1. *Avoid a “heads down” experience for the teacher.*

The teacher’s abandonment of the tablet during the third study brought to light the need to consider more carefully what information should be provided on the tablets, as this tends to require a “heads-down” focus, and what information should be provided on the walls or other surfaces (i.e., promoting a more heads-up focus). Reducing the amount of time the teacher needs to look down increases his ability to scan the room and interact with students.
2. *Large, dynamic representations of student work can provide ambient cues.*

These early studies showed the important role that large-format displays can have in supporting the teacher in making real-time orchestration decisions, by providing him at-a-glance insight into the work of the groups distributed around the room. Consistent with the principle above, these displays serve to promote a “heads-up” view of the classroom and can help the teacher decide where he or she is needed in the flow of the classroom activity.

3. *Notification and feedback about activity states should be actionable and timely.*

In supporting teachers and students in the orchestration of class activities, it is critical to understand how feedback and prompts fit into the flow of activities. Information or prompts that are not actionable or that disrupt the flow of activities should be reconsidered in terms of when occur in the script (or if they should occur at all). Providing the teacher with reports on how students had answered past questions was of little use to him or the students, as they had moved on to another task; hence, the use of a prompt that tried to re-engage them with “old” content was disruptive. Such a reporting feature would be better used after the entire activity, for purposes of class discussion (as seen in the second initial design study). On the other hand, providing the teacher with a prompt to review student work *prior to submission* might be a valuable means of engaging with students at a critical point in the activity. This example illustrates the need to think about timing and purpose in the design of such DTEL exchanges.

4. *Intelligent software agents can help coordinate the flow of activities and materials based on emergent class patterns.*
We were encouraged by the ability of the intelligent agents to manage the complex task of tracking student exposure to artifacts in the knowledge base in order to make real-time scripting decisions. It would have been unrealistic and unmanageable to require the teacher to remember what materials every student had worked with, their current group configurations, and their immediate resource needs. By offloading such tasks to intelligent software agents, we can not only free the teacher to focus on working directly with the students, but we can also leverage the agents’ own data mining abilities to make orchestrational moves based on the complex processing of individual student and whole class learning traces. Because of the time and cognitive resources they would require, such orchestrational affordances would be practically impossible in a paper-based curriculum.

Similar to Dillenbourg’s (2012) orchestrational design principles, these principles were extracted from multiple design studies in authentic classroom settings and frequent interactions with the teacher throughout their design and enactment. An important focus of these principles is the support of learning that is distributed across the students, various technology elements, and the physical learning environment. The inclusion of intelligent software agents further builds on the recommendations of Roschelle, Dimitriadis & Hoppe (2013), who note there is considerable promise in analyzing and acting upon the learning traces of individual, small group, and whole class interactions to support classroom orchestration.

**Pedagogical Design Principles:**

1. *Student inquiry should be informed by emergent, aggregate representations of the knowledge community’s progress*
Across all three design studies, aggregate representations played a significant role in supporting student problem solving and developing higher quality domain specific insights. We did however come to the conclusion that we need to be careful not to “give too much away” in these representations, and still leave sufficient room for students to develop their own extensions or interpretations of ideas, and ask questions about the information. We also gained some insight into how such aggregated forms of collective knowledge might support the formation of a cohesive knowledge community. By seeing their work aggregated with that of their peers – both in the visualization maps and the aggregated TAR pages – students were able to see their work as being part of a larger collective corpus of knowledge, and to monitor the progress of that collective representation. This suggests that well designed aggregates of emergent student knowledge can play a important role in supporting students in discussing and refining existing ideas, and developing new knowledge.

2. **Curricular scripts should be structured to include individual activities that feed into larger collective goals.**

Our initial design studies highlighted how the products of individual student work can be leveraged for larger group and class-wide goals. This was particularly evident during the third design study, where the groups who were able to leverage the aggregated work of their peers (while in the smart classroom), out performed both the individual students working at home and the groups who did not have access to the aggregated representations. Having individual students work on similar and/or connected aspects of a larger task, can provide a range of opinions, evidence, and
insight, which can then be used as a reference point for further discussion, debate, and refinement by the larger community.

3. **Students should be supported in critical reflection as both a product and a resource for the learning community.**

Building in supports for critical reflection played a significant role across all three initial design studies. During the TAR activities, students were scaffolded in order to focus their responses (including adding tags and text-based reflections) on the critical learning objectives of the activity. Follow-up activities were similarly structured to help ensure students reused these re-artifacts towards furthering the community’s knowledge. Without such support, students can often struggle to choose the correct strategies, areas of focus, or progression of tasks.

4. **Assigning expertise groups can help distribute knowledge across the community and provide support for further distributed tasks.**

Distributing responsibility for the overall community knowledge, through assigning expertise groups or areas of focus, can help divide up tasks within the class and provide opportunities for collaborative knowledge construction that builds on multiple perspectives. In the third design study, rather than having each student look at *every* homework problem we were able to divide the problems up among expertise groups in the class. During the smart classroom activity, students were able to bring this expertise to bear on the solving the problems their group hadn’t seen before. Although
these findings are preliminary, they suggest that distributing the task load and student expertise across the community may be an effective means of supporting more complex inquiry activities.

Principle 1 and 2 descend primarily from our original research interests in collective forms of inquiry, as investigated by Slotta and his colleagues (Slotta & Najafi, 2013; Peters & Slotta 2008). This research program is set within a broader area of interest in knowledge communities, as reviewed by Bielaczyc & Collins (2006), and others (e.g., Zhang et al, 2011). It is concerned with how best to engage students individually and collaboratively, so that the products of their inquiry contribute to a larger sense of progress and achievement at the community-level.

Principle 3 is concerned with the role of scaffolding environments for supporting inquiry through critical reflection, which is the topic of much research in the learning sciences (e.g., Linn & Slotta, 2009; White and Frederickson, 1998; Songer, 2006; Kirchner et al, 2004). Within a DTEL curriculum, such supports take on added importance, as students may take on new roles, and engage with the community across multiple learning contexts – some of which may happen outside of the direct supervision and guidance of the teacher. Principle 4 derives from seminal work by Brown and Campione (1996), concerning the role of structured scripts for supporting collective inquiry in a community of learners. It supports the interpretation of collective inquiry that no one member of the community has all the relevant knowledge, information or expertise, and that students must collaborate to leverage their individual expertise in solving the task.

Technological Design Principles:

1. Handheld computers offer increased mobility within the DTEL environment.
The introduction of handheld portable tablets was a major shift in how we instrumented the classroom (versus bulkier and less portable laptops). Although only the teacher was equipped with a tablet during the third study, his increased mobility highlighted the potential for increased movement of all participants in the learning environment.

2. Tracking users within a DTEL environment offers unique opportunities for ad hoc groupings and collaborations.

The ability to track individual users and groups allowed us to create “zones” within the physical space of the smart classroom, providing materials to students according to which part of the room they occupied. This allowed us to conceptualize the notion of “ad hoc” groupings – where students work together and share materials for a short time depending who is currently tagged as co-occupying a “zone” in the room (achieved by assigning students zone-specific metadata when they logged into a location). During these early designs, this was limited to providing all members in a group the same shared information; however, the use of intelligent software agents can allow for the introduction of more complex scripted interactions, such as where each student within a group could receive specialized prompts or materials corresponding to one component of a complex collaboration script.

3. Automatically updating devices based on real-time conditions can support rapid transitions within and between activities (e.g., feedback, delivery of materials, re-grouping of students)
Run-time “failures”, such as the teacher needing to refresh his laptop during the second study, highlighted the dynamic or ill-determined nature of the real-time activities in a DTEL environment. This required us to rethink the underlying architecture that updated the environment’s devices and displays. Our first attempt at this was with the teacher tablet during the third design study, which revealed student progression within the script as it happened. With increasingly dynamic and interrelated forms of student contributions, we expect this need for real-time updating to become critical element within DTEL curricula.

4. Small group interactions can benefit from the use of large, shared displays that support collaboration and idea refinement.

Giving students a large communal display to help focus their discourse seems to reduce the exclusion of more distal group members, and provides a common point of reference for discussion and debate. These patterns were consistent across all three studies, when comparing student groups who engaged with shared large-format displays with those forced to cluster around a single laptop screen.

Technology supports for student inquiry have been well chronicled in the learning sciences (Quintana, Zhang & Krajcik, 2005; Slotta & Linn, 2009; Hug, Krajcik & Marx, 2005). These technology design principles build on both this prior research and our own findings from the initial design studies, with a specific focus on distributed learning. In particular, these design principles highlight the increased awareness of the role the spatial environment, student mobility, and enabling interactions across multiple personal and collaborative devices can play in supporting learning in these kinds of environments.
3.5 Next steps

From these initial design studies, we gained some productive experience with DTEL technologies and pedagogical designs, some positive findings about student engagement and learning outcomes, and some discrete principles that could help inform more substantive designs. Still these studies were of limited duration and scope, and not sufficient to engage a classroom of students in a sustained knowledge community approach. Developing a more substantive curriculum presents a greater design challenge, which will benefit from these preliminary studies. Chapter 4 outlines the design of the method of this doctoral research, where a 3-month physics curriculum was developed according to the KCI model, and the S3 framework was created to support our curricular designs, resulting in a DTEL environment that encapsulated the pedagogical and epistemic principles of KCI.
Chapter 4: Methods

4.1 Ethical Considerations

My doctoral research is part of an ongoing SSHRC-funded project on “New Ways of Teaching and Learning in Technology Enhanced Classrooms”, led by my research supervisor, James Slotta. Ethical approval for the SSHRC funded research was obtained from the University of Toronto’s Office of the Vice President, Research in June 2008 (Protocol Reference # 25178).

Students and their parents were provided with an information letter outlining the research study, and consent forms for permission to be part of the study, to be video recorded, and to be interviewed as part of the study. Subsequently, they received an updated consent form granting us permission to make edited video from the culminating activity publicly available to showcase our work. The teacher was also given a consent form in which he agreed to be a part of the study and to be videotaped. All of the consent forms were printed out and given to the participants before the study, with the exception of the permission form allowing videos to be made publicly available, which was given to the students a week before the culminating activity. Because the students were minors, a parent or guardian signature was also required on each consent form.

In the letter outlining the research study, students were informed that participation in the study was entirely voluntary, and that participation in no way affected their grade in the course. Students were informed that their names would be kept confidential and pseudonyms would be used in any research reports. During the post-unit interviews students were informed again that their participation was voluntary and they could stop the interview at any time without negative consequences.
To maintain students confidentiality, they were given the opportunity to choose individual login nicknames. I also assigned students new pseudonyms (distinct from their chosen login names) for research and analysis purposes. Both environments, PLACE.web and PLACE.neo, were password protected, limiting access to the research team (myself, my supervisor, and a technologist), the students, and the teacher.

4.2 Role of the Researcher

I participated directly in the design and implementation of the physics curriculum across both classes. I was also actively involved in the design and development of the S3 technologies, working closely with the technologists (and performing some small coding tasks). Throughout the study, I was a permanent member of the co-design team.

In the design phase, I worked closely with my supervisor to develop the scripted activities and orchestral scaffolds to be enacted during the curriculum. During co-design meetings, we discussed these interventions with the teacher, and worked as a team to make them part of an effective curriculum. During the implementation phase of the project, I was a regular observer in the classrooms. Throughout the intervention, I worked closely with the teacher and technologists to address technical issues and to make small adjustments to the script as necessary.

The remaining sections of this chapter focus on describing the SAIL Smart Space technology framework that was developed to enact our design (in the form of two complementary technology platforms), as well as the specific intervention, with a focus on the culminating smart classroom activity, and data sources.
4.3 S3 – Developing a Technology for Supporting KCI in Smart Classrooms

In order to successfully enact the kinds of complex designs required for KCI, we needed a flexible and adaptive infrastructure that could support the design and orchestration of collaborative activities that included spatial, social, and semantic dependencies. To this end, a central part of this research was the design and development SAIL Smart Space (S3), an open source framework that coordinates complex pedagogical sequences, including dynamic sorting and grouping of students, and the delivery of materials based on emergent semantic connections. One of the main goals in the development of S3 was to allow the physical space of classrooms, or other learning environments, to play a meaningful role within the learning design – either through locational mapping of pedagogical elements (e.g., where different locations are scripted to focus student interactions on different topics) or through orchestrational support (e.g., where physical elements of the space, like projected displays, help to guide or coordinate student movements, collaborations or activities). We also wanted S3 to add a level of intelligence to the learning environment, including real-time data mining and computation performed by intelligent agents to support the orchestration of inquiry scripts. The design of S3 also aimed to investigate the role of ambient displays of information within the physical environment, as a means of providing “peripheral” guidance or feedback to students and teachers alike.
In designing S3, we developed a suite of five core technologies: (1) a portal for student accounts and software application management; (2) an intelligent agent framework for data mining and tracking of interactions in real time; (3) a central database that houses the designed curriculum and the products of student interactions; (4) a visualization layer that controls how materials are presented to students; and (5) a communication framework for connecting the products of student work (e.g., notes, polls, and multi-media) and tangible and physical inputs (e.g., Arduino or other sensors and probes) (see Figure 8). Our goal in developing S3 was to support a broad program of research on collaborative inquiry, allowing for more rapid development of learning.

Figure 8: SAIL Smart Space (S3) systems architecture, showing the use of direct WebSocket messaging to enable communications amongst any element of the environment, a persistent, non-relational (no SQL) database (MongoDB) and intelligent agents.
materials and environments. While it is not designed as an off-the-shelf solution, S3 is offered as an open source framework, with hopes of promoting wider access to such functionality, and growing a community of developers within the learning sciences (Slotta et al, 2012). Sections below describe the methods of designing the physics curriculum that would instantiate S3, as well as the intervention that would evaluate our success.

4.4 Developing a Persistent Knowledge Community for High School Physics

After conducting the three preliminary design studies described above, we returned to the challenge of supporting KCI, and the goal of a general technology framework that could potentially support related designs and curricular enactments in future research (by ourselves and collaborators). To this end, and working with our co-design teacher, we developed a 12-week physics curriculum based on the KCI principles (e.g., the need for a collaboratively constructed knowledge base) that engaged students across several contexts: (1) their classroom; (2) their homes; (3) field observations; and (4) a “smart classroom” (different from their classroom), where they engaged in carefully scripted interactions with an array of media and materials.

Our goal for S3 was to provide an orchestrational framework that included the use of social tagging, metadata, and intelligent agents and data mining to support the enactment of collaborative inquiry scripts. In order to support these kinds of activities we needed to build the technology infrastructure that would allow us to develop the necessary physical materials, activities, and scaffolding technologies (discussed in 4.2 above). Because our partner teacher was working in the domain of physics (11th grade), we sought to design a KCI-based physics curriculum where smart classroom technologies supported collaborative and collective forms of inquiry for students, and supported critical reflection and formative interventions for the teacher.
Two main goals were identified by the teacher: First he wanted to help students to recognize “physics in their everyday lives” and bring this view of physics back into the traditional classroom setting; Second, he wanted students to develop a coherent understanding of the underlying principles of the course, including the connections amongst those physics principles (i.e., to “see that all the principles are tied together”). The teacher’s goals for the intervention matched many of the curricular expectations from the Ontario Science Curricular Guidelines for grade-11 physics including, having students: (1) use the appropriate scientific models to explain and predict the behavior of natural phenomena; (2) analyze and synthesize information for the purpose of identifying problems for inquiry, and solve the problems using a variety of problem solving skills; and (3) locate, select, analyze, and integrate information on topics under study, working both independently and as part of a team.

4.4.1 Participants and setting.

The same researchers, technologists, and co-design teacher participated (i.e., as in the initial design studies described in Chapter 3) in this version of the intervention. This study involved two classes of grade-eleven physics students totaling 45 students: 22 in one class and 23 in the other.

4.5 Physics Learning Across Contexts and Environments (PLACE)

We needed to support student interactions within the community, including collaboration with peers and access of the knowledge base at home, in their neighbourhoods, and in the classroom (i.e., for purposes of completing of homework problems, uploading examples, and tagging and discussing the contributions of peers). To this end, we developed two complementary systems: PLACE.web. (Physics Learning Across Contexts and Environments), a collaborative social
network, focused on the domain of physics, where students contributed content, engage with the work of their peers, and complete tasks assigned by the teacher; and PLACE.neo, a smart classroom environment that orchestrated the activity, making use of the PLACE.web content. In order to support students across both these systems, we needed to develop several foundational elements to S3, including Rollcall, a user portal that provided each student a personal profile and nickname, which also allowed them to personalize their identity within the community. Below I describe specific software elements we developed for both PLACE.web and PLACE.neo.

4.5.1 PLACE.web.

The PLACE.web learning environment supported students as a knowledge community through five different interaction spaces: (1) The student status page; (2) The contribution upload page; (3) The user contribution discussion pages; (4) The assigned homework pages; (5) And the “Associative Web” -- a semantically aggregated visualization of the entire community knowledge base. Additionally, the teacher was provided with a set of support tools, and built-in assessments. Each of these items is described in detail below.

*The Student Status Page* – This was the first page that students saw when logging into PLACE.web, and was broken into several distinct information spaces giving the student a quick overview of their contributions and the state of the overall class activity.

The status page showed several newsfeeds of the whole class’ contributions (Figure 9), and their personalized “Comment Score” and “Tag Score,” which tracked the aggregated totals of the votes students had received from their peers for their contributions.

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The contribution upload page – This was where students uploaded their contributions (video, picture, or narrative) to the shared knowledge base. The contribution upload page was designed to be as device agnostic as possible (i.e., Windows, Mac, Android and iOS compatible) allowing students to upload and create content in a broad range of contexts (at home, in their neighborhoods, at school).

The discussion pages – These were designed to allow students to engage in discussion and debate, and to vote on the principles tagged to the contribution. These interactions took the form of threaded discussions, which included aggregated votes for each of the principles (Figure 4).

Figure 9: An example of a contribution discussion page with (1) a student uploaded video, (2) student submitted principle tags and voting, and (3) threaded student discourse
The assigned homework pages – These pages were teacher-created and centered on multiple choice homework problems. The homework page was structured similarly to the discussion page; however, on the homework pages, peers’ contributions were not shown to students.

The Associative Web – The Associative Web was an interactive, filterable visualization that used the “principle tags” metadata to semantically connect all the contributions of the knowledge community. The Associative Web allowed students and teacher alike to view the knowledge base as a cluster of student contributions for the purposes of finding artifacts tagged with specific principles and connections between seemingly disparate examples.

Teacher Support Tools – The teacher was provided with a front status page similar to the one seen by the students, and an authoring page that allowed him to create multiple-choice homework problems.

Built-in Assessments – The teacher also had access to a customized assessment tool on each contribution and homework page, through which he could provide students with a mark (from 1 to 4) and personalized feedback. The assessment tool also allowed the teacher to write himself personal notes, which he could later review to help in adjusting upcoming lessons.

Individual Student Reports – The teacher could also view a single page that provided detailed information on each student’s activity on PLACE.web, including links to his or her individual contributions, and their total and average marks from his assessments of their work.
4.5.2 PLACE.neo.

To scaffold the different contexts (at home, in class, in the smart classroom), and interactions (individual, cooperative, collaborative) we required specific supports for each stage of the activity, including connecting student activities with the knowledge base and with each other in real-time. Guided by the findings of the preliminary studies, we developed PLACE.neo as a technological pedagogical environment that could support the design of a curriculum script in a DTEL environment. Below I briefly describe the elements developed for each stage of the activity.

*Figure 10: Students engaging with the interactive displays and individual tablets in the smart classroom*
PLACE.neo: At-home phase: In order to facilitate the at-home portion of the script, and capitalize on students’ familiarity with the platform, this first stage employed PLACE.web, with a new icon added to the existing student status page for students to access the activity.

PLACE.neo: In-class phase: We developed a context-specific tablet application that connected students to their peers in real-time, and used the aggregated products of the previous at-home phase. Intelligent software agents were employed to coordinate the distribution of materials and to ensure each group reached consensus.

PLACE.neo: Smart classroom phase: For the third and final stage of the culminating activity, we developed a set of tools that took advantage of the physical and collaborative affordances of the classroom, including large projected displays accompanying each station, and individual tablet computers to support students as they performed activities. The large-format interactive displays aggregated the products of individual student work (from their tablets) and helped facilitate group discussion (Figure 10). S3 software agents queried metadata to provide students with context specific tasks and materials, facilitated the dynamic grouping of students, and ensured consensus was reached on all collaborative tasks. We also developed a set of ambient displays that showed real-time information on the state of class activities, and an orchestration tablet that provided the teacher with additional procedural information and control over the progression of class activities.

4.5.3 Collective inquiry: Designing for coherence and knowledge community.

In order for this intervention to be seen by the teacher and students as more than a supplemental activity, we needed to develop a complete curriculum in which the smart classroom was one of
several learning contexts, integrated with activities in the classroom and home environments. In order to investigate how the smart classroom could leverage student-contributed content for authentic learning activities, we also needed the curriculum to produce artifacts that could be reused in meaningful ways. A detailed curricular “script” was designed, delineating the specific activities, materials, sequences and conditions that constituted a coherent inquiry curriculum where students worked collectively as a knowledge community, aggregating resources, working across contexts and informing their own inquiry.

We began by generating, with the teacher, a list of fourteen principles (Table 1) that covered the first three units of the course: (1) Kinematics, (2) Forces and Motion, and (3) Work, Energy, and Power. We then developed a script that engaged students with these principles by requiring them to capture examples of physics in the world around them (either through videos, pictures, or text). Students then uploaded their example to the classroom database, “tagged” with any of the principles they felt to be applicable, with a written explanation for their choice of tags. The wider community of students was encouraged to respond to these user-contributed artifacts: debating tags or explanations, voting, and adding new tags – with the stated aim of developing consensus about each item.

Table 1:

Grade 11 Fundamental Principles for Kinematics, Force and Motion, & Work, Energy, and Power

<table>
<thead>
<tr>
<th>Vectors</th>
<th>Acceleration</th>
<th>Fnet = 0</th>
<th>Kinetic Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newton’s First Law</td>
<td>Uniform Motion</td>
<td>Fnet = Constant (non-zero)</td>
<td>Potential Energy</td>
</tr>
<tr>
<td>Newton’s Second Law</td>
<td>Kinetic Motion</td>
<td>Fnet = non-constant</td>
<td>Conservation of Energy</td>
</tr>
<tr>
<td>Newton’s Third Law</td>
<td>Friction</td>
<td>Static Friction</td>
<td></td>
</tr>
<tr>
<td>Law</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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To support this process, we developed a script (i.e., a specified sequence of curricular activities) that required students to complete three steps: (1) voting on existing tags and/or adding a new tag, (2) voting on the contributions of their peers, and (3) adding a reflection or rationale of their own. This was designed to ensure that students covered three key aspects (focus on the principles, reflecting on the work of their peers, and adding their own thinking). As part of the script, in order to ensure that all the principles were covered and to encourage students to become experts in particular principles, we assigned each student to an “expert group” in which they were assigned a subset of the principles (e.g., Newton’s First Law, Vectors, and Potential Energy) for which they were responsible to keep updated (i.e., to make sure all relevant items had been tagged, and add a comment where they felt the principles had been wrongly tagged).

For each of the three units within the curriculum (Kinematics; Force and Motion; Work, Energy, and Power), students completed this script at least once, in which they were tasked with uploading at least one example and commenting on at least two of their peers’ submissions (with a focus on their expert principles). At the end of each unit, the teacher selected some examples to discuss with the class, and had the students look over examples that had been tagged with their principles, to add to their discussion. Students also uploaded results from their in-class laboratory experiments to the knowledge base, tagging their reports with principles and adding reflections on their methodologies – which other students were also free to critique. For homework, the teacher provided multiple-choice problems, which students solved using a script similar to the one used for their contributions: tag, answer, and reflect (TAR) on the problem. All student contributions went into the collective knowledge base, which itself served as a basis for various
further activities. For example, students were asked to develop “challenge homework problems” for their peers, using examples drawn from the knowledge base.

The teacher’s role in this phase of the curriculum was also scripted, in the sense that he was expected to upload regular homework problems, review and assess student answers, and adjust class lessons accordingly. He was also expected to review student contributions, to find examples or interesting discourse for use during in-class discussions.

**Scripting complex inquiry in a DTEL Environment: A Culminating activity for PLACE.**

As a culminating activity in the PLACE design, we created a challenging task where students had to analyze the physics of Hollywood movie clips, including setting up physics problems to test their validity. This culminating activity (using the PLACE.neo technology) involved three short-term scripts that spanned home, a traditional class setting, and a smart classroom, and relied heavily on S3 agents to coordinate the distribution of materials, roles, and tasks.

**Pre-activity: At home.** At home, students were tasked with looking at a collection of the problems they had been assigned during the proceeding 12-weeks (including their contributed challenge problems and new problems developed by the teacher), verifying their tagging of relevant physics principles, and adding equations that might be used to solve the problems.

**Pre-activity: In the classroom.** In-class, students worked in small groups, using tablet computers to reach consensus on a refined “final set” of the tags and equations for each problem. The goal of this activity was for students to achieve consensus about the principles and equations that had been assigned to each problem in the corpus. The group was assigned one of the problems, with
each student seeing the problem and its various tags on his or her tablet (from the individual at-home activity), and asked to agree or disagree. The group was required to reach consensus on all of the principles and equations before they could move to the next problem. Students could see the work of their group members in real-time, reflected on their own tablets, which helped facilitate face-to-face discussions. The resulting set of problems, tagged with principles and equations, were then stored in the knowledge base as a prepared set of materials for use within the final smart classroom script.

**Main Activity: In the smart classroom.** Upon entering the smart classroom, students were engaged in solving a series of ill-structured physics problems using Hollywood movie clips as the domain for their investigations (e.g., could Iron Man Survive a fall to earth, as depicted in the movie?). Four videos were presented to the students, each at a distinct physical location within the room. The students were engaged collectively, working as a whole group of 12-16, as well as collaboratively, in various small group configurations as directed by the S3 intelligent agents (See Section 5.4.1 below). The smart room script was broken up into four different steps as shown in Figure 11: (1) Principle Tagging; (2) Principle Negotiation and Problem Assignment; (3) Equation Assignment, and Assumption and Variable Development; and (4) Solving and Recording. In each step, students moved from one video to another, completing a set of collective and collaborative tasks that built upon the emerging knowledge base, using tablets and large format interactive displays.
Figure 11: The smart classroom Hollywood Physics script involved four distinct steps. The dark blue boxes indicate actions mediated by intelligent software agents.
Step One: Principle Tagging. Each student received a set of three or four principles (i.e., out of the 14) on their tablet, which were determined by querying that student’s prior expertise groups. The students were asked to go to one video at a time, and to “swipe” any of their four principles that they found relevant to the video onto the large display at that station. After 4 two-minute intervals, all students had tagged each of the four videos with any of the principles that were relevant. Because each principle had been assigned to at least two students, there were multiple instances of the principles on the boards (see Figure 12).
Step Two: Principle Negotiation and Problem Assignment. S3 agents equally assigned students to one of the video boards based on the frequency of their tagging. Once all students had arrived at their assigned stations, the teacher “advanced” the script using his tablet, and students received their task: first, they negotiated the final principles for their video; next, after confirming that they had reached consensus about the principles, they were provided with all physics problems that had been tagged with those principles in the previous (in-class) activities. The problems were distributed amongst the individual group members, who made simple “yes or no” decisions about whether the problem might be an interesting model for how to set up solving the video (Figure 13). Each student had to promote at least one problem to the negotiation board from their set (Figure 14), encouraging all group members to take an active role in setting up the problem. Additionally the movement between the “private” space of the tablet and the public and collaborative space on the interactive walls aimed to have students work in multi-modal contexts within the activity.
Step Three: Equation Assignment and Assumption and Variable Development. Students are reassigned to new video stations (see Figure 11: “Sort 2”), based on the criterion of grouping students who had not worked together in any previous step. Once at their new location, individual group members were given a subset of the negotiated problems from Step 2, and shown the equations connected to the problem during the in-class portion of the script. Students promoted those equations they felt might help in solving the video challenge (Figure 15) to the shared display and negotiated a “final set”. Group members then individually came up with assumptions and variables to fill in any information “gaps”, and engaged in the negotiation and consensus script to produce a final set (Figure 16). Unlike with the other negotiation and consensus tasks, when a group submitted a final set of assumptions and variables, the teacher was alerted on his orchestration tablet to review students work and either approve it or to send them back to refine their submission.
Figure 15: Step Three, Equation Assignment task – Left, individual student tablet showing equations connected to the negotiated problems from Step Two for promotion to the interactive display (as seen on the Right).

Figure 16: Step Three, Assumption and Variable task – Left, Students can promote free-form text Assumptions or Variables to the interactive displays (as seen on the Right)
Step Four: Solving and Recording. In the final step, student groups used the collaboratively constructed scaffolds on the interactive whiteboards for support, and with pen and paper solved their challenge problem and recorded their final answer as a video narrative using the tablet’s built in camera.

4.6 Data Sources

It is often recommended that research include multiple data sources in order to triangulate data and corroborate findings (e.g., Greene, 2006; Mason, 2006, Johnson et al., 2007). The use of multiple data sources is particularly relevant in design-based approaches, due to the complexity and innovative nature of their design and enactment (DBRC, 2003). To this end, this project included data from both the teacher and the students across numerous sources, described below.

4.6.1 Pre- and post-questionnaires.

Before introducing students to PLACE.web, we wanted to collect a baseline measure of their understandings of the physical principles, including their application to experiences outside of the classroom, and their beliefs about the value of collaboration. In order to evaluate these elements, we developed a questionnaire that consisted of two sections (See Appendix F):

- Section One consisted of three open ended questions, two that aimed to elicit students’ understanding of the physics principles involved in real world examples (i.e., A cyclist pedaling up a hill), and one that asked students to explain why it was important to know the underlying principles (i.e., and not just the formulas).
• Section Two involved seven questions that were a mix of open-ended and Likert scale questions that investigated students’ perceptions of working with peers, their use of science in their everyday lives, and the use of technology for learning inside and outside of school. These questions adapted from a similar instrument developed by Najafi & Slotta (2012) that was used to examine students’ perceptions within a technology-enhanced KCI curriculum.

The questionnaire was printed out and given to students just prior to the introduction of the intervention and students hand wrote their answers.

For the post-intervention questionnaire, two more open ended questions were added that asked students to reflect on the technology environments (PLACE.web and neoPLACE), if they helped the students to collaborate with their peers in developing understandings of the course content. The questionnaires were printed out and were to be given to the students. However due to a special external event during that day’s class many of the students were not in class to complete it. The questionnaire was then digitally hosted online for students, which some did log in to complete.

4.6.2 Server logs of class activities.

Because all activities took place within the S3 PLACE.web and PLACE.neo platforms, we were able to capture a rich array of data on when students or the teacher were logged into the learning space, what (and who’s) content they were working on, and their actions on that content (e.g., adding new content, replying to a comment, voting on a tag). This data can help us in understanding the kinds of practices that the platform fostered within the community and its
effectiveness seamlessly connecting student work in their neighbourhoods, at home, in class, and in the smart classroom.

The S3 infrastructure also allowed us to track all the moves made by the S3 software agents in tracking and responding to student and teacher actions. Of particular interest to this research is how the agents facilitated student tagging of principles and equations during the in-class portion of the culminating activity (e.g., the bucket agent and consensus agent). Also, during the smart classroom activity, it was of interest how the agents responded to class activities to provide semantically relevant scaffolding materials (bucket agent), ensured that students came to consensus on debated materials (consensus agent), sorted students based on their past actions (student sorting agent), and alerted the teacher when it was time to approve student work (student progress agent). Analysis will focus on how these agents helped reduce the orchestrational load of both teachers and students.

### 4.6.3 User-contributed content in the knowledge base.

Three types of user-contributed content were of interest:

- **Student-Contributed Examples** can provide insight into how students connected the physics “inside” the classroom with their “everyday” lives. Analysis will address whether or not students were able to find examples of physics in the everyday, and whether or not they were able to build on the examples contributed by their peers.

- **Student Discourse on Examples** can give us insight into the evolution of student understanding around the examples submitted by their peers. Because students were
required to periodically review their submissions, the student’s own level of understanding can also be examined.

- **Student-Generated Challenge Problems** are of value to this research as a way of examining how students used existing peer-contributed content to create new artifacts for further knowledge building and learning.

4.6.4 Video recordings of culminating activity.

All four runs of the culminating smart classroom activity were recorded using seven video cameras (one for each zone in the room, one roaming camera, a fixed position camera, and a ceiling mounted dome camera), and sound recordings were captured using five miniature voice recorders and a lapel microphone worn by the teacher. All six screens in the room (the four large-format displays at each zone, the ambient display, and the aggregate display) were recorded using screen capture software. The individual zones’ voice recordings have been transcribed so we can investigate both the discourse between students and between the teacher and the individual groups. Analysis of the captured video and transcripts will focus on how the various S3 technologies supported student collaboration and teacher orchestration. Particular focus will be placed on any new orchestrational patterns that arise from the S3 technologies.

4.6.5 Culminating activity group worksheets.

The student worksheets generated during the final step of the smart classroom activity can be examined to understand the efficacy of the user-generated content on the large-format displays as a resource for scaffolding student problem solving. The final products of each group can be compared to see the frequency in which items appear across both spaces (indicating use of the
large format display to scaffold student work). The worksheets will also be analyzed to assess student fluency in the physics concepts under investigation. Transcripts of student conversations will be used as a means of triangulating these findings.

4.6.6 Pre- and post-unit teacher interviews.

Both pre- and post-unit interviews involved semi-structured face-to-face interviews with the teacher in order to collect qualitative data on his experience with the curriculum and technology. The pre-unit teacher interview focused on problems that the teacher identified with current approaches to the teaching and instruction of physics, his personal goals for the intervention, how the intervention might change students’ conceptualizations of physics, and how the PLACE technology would affect his own teaching practices. The post-interview focused on asking the teacher to reflect on his experiences with the various technologies, their actual effect on his teaching practices, their effect on his classroom orchestration, his perceived changes in students’ ability to connect physics to the fundamental principles and to life outside the classroom, and any challenges or shortcomings of the intervention that he would like to see improved.

4.6.7 Post-unit student interviews with volunteer students.

As with the teacher interviews, the student interviews were face-to-face and involved a series of semi-structured open-ended questions. Nine students from across both classes volunteered to be interviewed about their experiences with the curriculum and the various PLACE technologies. As part of the interview, students were asked to describe the curriculum in their own words to understand their perspective on the design. Additional questions aimed to elicit any changes in
their perspectives on physics in their everyday lives and their views on the S3 technology elements’ effectiveness in supporting collaboration, engagement, and orchestration.
Chapter 5: Analysis and Results

5.1 Designing S3 to Support KCI Curriculum

The primary goal in developing S3 is to create a Distributed Technology Enhanced Learning (DTEL) environment to support student inquiry. Following the earlier review of theoretical and empirical research, KCI provided a suitable pedagogical model for developing such a curriculum, which in turn provided requirements for the technology-enhanced environment, described in Chapter 4. The first analysis seeks to validate the design of S3 according to the KCI principles. That is, it will demonstrate that the S3 technological elements provided affordances that are required by the KCI pedagogical principles. Once this is established, we can be confident that the S3 environment deeply embodies the epistemic commitments central to KCI, and hence to one valid example of a DTEL pedagogy.

To this end, I review how each of the 4 KCI design principles were explicitly accounted for in the design of S3. For each principle, I begin by identifying the specific features and design commitments made in S3 to accommodate that principle. Then, I analyze how S3 was able to support that principle in specific design features of the PLACE curriculum. Next, I analyze the enacted curriculum, to confirm that the targeted DTEL features (learning interactions and affordances) were actually enabled. In this way, the analysis will demonstrate that S3 constitutes a DTEL environment, with specific commitments to pedagogical and epistemic forms that are central to DTEL curriculum. Once this is established, an analysis of student learning and interactions in PLACE can be said to bear on the more general class of DTEL curricula (see Figure 17).
5.2 Analysis of KCI Principle #1: Students work collectively as a knowledge community, creating a knowledge base that is indexed to a specific content domain.

5.2.1 S3 design: Supporting Principle #1.

In order to support this principle, we needed to develop a database model that would allow for new objects, relationships, and semantic structures to be added as the inquiry project progressed. Over the course of the activity, new themes might emerge and new elements of the content domain might open up for student inquiry, requiring new (i.e., unforeseen) metadata (i.e., categories or tags) and ways of connecting related artifacts in the knowledge base. In response, we chose to develop the S3 database using a non-relational “NoSQL” database platform called MongoDB. We also employed a JSON (JavaScript Object Notation) based Document-Oriented approach, which is well suited for supporting KCI as it does not require every document in the database to have the same metadata fields (see Figure 18 below). This means that new information can be added to some records in the database without updating all records. For example, within an inquiry curriculum that is based on emergent community themes, students in the class might decide that all new contributions should to be classified according to a scheme of
“Question”, “Idea”, or “Argument.” Rather than requiring the system (or technicians) to go back and add this relationship to all the objects already in the database, a Document-Oriented approach has the flexibility to ignore the relational discrepancy.

```
{
    AuthorName: "Sue",
    Class: "Phys003",
    ContributionType: "Reflection"
}
{
    AuthorName: "David",
    Class: "Phys003",
    Tags: [
        "Newton’s First Law",
        "Vectors",
        "Acceleration"
    ],
    ContributionType: "Video",
}
```

*Figure 18: Two examples of “Documents” in MongoDB. Although the two documents have the same type (“Phys003”) and share some elements, they can also have unique elements (tags). This allows for flexibility in the growth of objects in the database, and for objects to have a relationship to some objects but not others.*

In a similar vein, new metadata can be easily assigned to existing records only as needed. Adding a new layer of folksonomy (student generated tags) would simply require adding the relevant key/value pair to the necessary items in the database (e.g., as students tag them). This approach allows curriculum designers to set up some defined relationships between objects in the S3 knowledge base at the outset (e.g., the 14 Physics Principles), but also allows a great deal of flexibility for new relationships, or social and semantic metadata to be added as the curriculum progresses.

From past designs, it became clear that as the knowledge base grew it would be increasingly difficult for students to retrieve (or be sent) content domain specific materials to support their
context or task specific inquiry needs. The development of intelligent data mining and software agents offered up a solution that could quickly retrieve and aggregate these materials from the knowledge base. The NoSQL approach can also facilitate the use of real-time data mining and software agents (i.e., as compared with traditional SQL databases) as it allows for faster querying and retrieval of data (Han et al., 2011).

5.2.2 S3 implementation: How PLACE supported KCI Principle #1.

This section describes how S3 was implemented in the form of a technology environment for PLACE, with a focus on the requirements of KCI Principle #1. Drawing upon the S3 feature of open metadata, we established a data model that explicitly included the 14 physics principles. For each activity, we developed interfaces and scripting logic that required every student attend to the principles (either through adding tags or voting on existing tags - see figure 19). This ensured that all student contributions were connected through this metadata. During the curriculum’s enactment the flexibility of the S3 database allowed us to add a new principle (Work), and remove another (Fnet = non-constant) based on the teacher’s perceived value of them for supporting student investigations.

To support both the teacher and the students in contributing to the knowledge base, we created five distinct content types, each with their own authoring tools, metadata; and aggregate views: 1) Examples; 2) Lab Reports; 3) Homework Problems; 4) Challenge Problems; and 5) Culminating Activity Problems. The creation of these unique content types allowed the knowledge base to be organized for easier filtering and visualization in the newsfeeds and the Associative Web.
For the culminating activity, we wanted students to review the principles and add equations for only a subset of the overall knowledge base. With S3, instead of having to restructure the database to support this selective use of resources (and only for the subset of data), we were able to simply add a new semantic tag to those objects (indicating their use for the culminating activity). This also made it easy for the S3 intelligent agents to work on the data (i.e., to distribute them to groups), as the agents only needed to look for objects tagged for use during the culminating activity (and could ignore the rest). At present, tagging objects for use in specific activities must be hard coded, however a goal of S3 is to allow a teacher to select the elements her/himself adding a greater level of orchestrational freedom.
5.2.3 S3 evaluation: Supporting KCI Principle #1.

The evaluation of S3 in supporting KCI Principle 1 is organized according to four distinct features: (1) connecting student-contributed content to social and semantic metadata; (2) bridging and interconnecting elements across units; (3) differentiating object types in the knowledge base (e.g., student uploaded examples, teacher submitted homework, student generated challenge problems); and (4) encouraging students to engage with a broad range of principles.

1. Connecting student-contributed content to social and semantic metadata.

To evaluate the first feature, we can examine how the knowledge was distributed across the fourteen principles. We looked at how the principles were distributed across all of the student-generated artifacts in the knowledge base. Table 2 shows the number of student-contributed examples connected to every principle. On average, 6.01 principles were connected to each example, with a SD of 2.7 (and conversely 82 examples were connected to each principle on average), which supports the interpretation that PLACE.web supported students in connecting their work to the fundamental principles of the course.

Table 2

<table>
<thead>
<tr>
<th>Vectors</th>
<th>Newton’s 1st Law</th>
<th>Newton’s 2nd Law</th>
<th>Newton’s 3rd Law</th>
<th>Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform Motion</td>
<td>38</td>
<td>8</td>
<td>97</td>
<td>94</td>
</tr>
<tr>
<td>Kinetic Friction</td>
<td>77</td>
<td>54</td>
<td>Fnet = 0</td>
<td>48</td>
</tr>
</tbody>
</table>
2. Bridging and interconnecting elements across units.

![Graph showing student tagging of principles by date across both classes, with each line corresponding to a different principle (e.g., the pink line at the top of the graph is shows vectors). The graph shows steady growth of the principles throughout the curriculum with some distinct peaks at the end of each unit. Of note is that all the principles are being attended to throughout, and not just those in the unit at hand (for instance Kinetic Energy is consistently tagged even thought it was part of the third unit).](image)

Over the course of the intervention, students were regularly engaged with all 14 principles (Figure 20). Although some principles took longer to gain traction (mainly due to the fact that

<table>
<thead>
<tr>
<th>Principle</th>
<th>Tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fnet = non-constant</td>
<td>50</td>
</tr>
<tr>
<td>Kinetic Energy</td>
<td>10</td>
</tr>
<tr>
<td>Potential Energy</td>
<td>4</td>
</tr>
<tr>
<td>Conservation of Energy</td>
<td>63</td>
</tr>
<tr>
<td>Acceleration</td>
<td></td>
</tr>
<tr>
<td>Conservation of Energy</td>
<td></td>
</tr>
<tr>
<td>Fnet = 0</td>
<td></td>
</tr>
<tr>
<td>Fnet = constant (non-zero)</td>
<td></td>
</tr>
<tr>
<td>Fnet = non-constant</td>
<td></td>
</tr>
<tr>
<td>Kinetic Energy</td>
<td></td>
</tr>
<tr>
<td>Kinetic Friction</td>
<td></td>
</tr>
<tr>
<td>Newton 1st Law</td>
<td></td>
</tr>
<tr>
<td>Newton 2nd Law</td>
<td></td>
</tr>
<tr>
<td>Newton 3rd Law</td>
<td></td>
</tr>
<tr>
<td>Potential Energy</td>
<td></td>
</tr>
<tr>
<td>Static Friction</td>
<td></td>
</tr>
<tr>
<td>Uniform Motion</td>
<td></td>
</tr>
<tr>
<td>Vectors</td>
<td></td>
</tr>
</tbody>
</table>
they were formally introduced in chunks, with each new unit), all of them saw regular use throughout the design. The graph also indicates that although there are some distinct flat areas (especially right after students’ first foray into PLACE.web), and some spikes (right when an activity was due), student participation within the community had persistent and sustained activity. Table 3 shows the overlap of principles across units, with 525 principle tags occurring within and 539 tags occurring outside of their assigned units. This nearly 50/50 split in the student engagement of principles (within and outside of their assigned unit) shows how PLACE was able to support students in connecting elements across units, giving them a more complete understanding of physics as a complete and interconnected series of ideas (rather than as isolated and discrete curricular blocks).

Table 3

<table>
<thead>
<tr>
<th></th>
<th>(a)</th>
<th>(b)</th>
<th>(a)</th>
<th>(b)</th>
<th>(a)</th>
<th>(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vectors</td>
<td>44</td>
<td>88</td>
<td>62</td>
<td>19</td>
<td>36</td>
<td>68</td>
</tr>
<tr>
<td>Newton’s Third Law</td>
<td></td>
<td></td>
<td>62</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>33</td>
<td>90</td>
<td>41</td>
<td>7</td>
<td>32</td>
<td>31</td>
</tr>
<tr>
<td>Fnet = 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>41</td>
<td>7</td>
</tr>
<tr>
<td>Uniform Motion</td>
<td>19</td>
<td>19</td>
<td>27</td>
<td>23</td>
<td>11</td>
<td>42</td>
</tr>
<tr>
<td>Fnet = non-constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27</td>
<td>23</td>
</tr>
<tr>
<td>Newton’s First Law</td>
<td>63</td>
<td>34</td>
<td>44</td>
<td>19</td>
<td>22</td>
<td>55</td>
</tr>
<tr>
<td>Fnet = Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>44</td>
<td>19</td>
</tr>
<tr>
<td>Newton’s Second Law</td>
<td>61</td>
<td>33</td>
<td>30</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conservation of Energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>11</td>
</tr>
</tbody>
</table>

Exit interviews with the teacher revealed that, prompted by the availability of the principles from the outset, students did attempt to discuss and debate some principles prior to their formal introduction in the curriculum, providing fertile ground for in-class discussion.

3. Differentiating object types in the knowledge base.
Overall, the PLACE.web infrastructure was successful in supporting the teacher and students in contributing a wide range of content to the knowledge base. The open metadata approach in S3 allowed these items to differentiated in the database for filtering and reuse – a critical element in supporting the other principles below. Table 4 shows both the different content types created and media formats used by students and teacher over the course of the PLACE.web portion of the curriculum. Similarly, during the smart classroom activity, each zone’s video wall was able to support the visualization and aggregation of multiple content types, including principles, equations, variables, assumptions, and the Hollywood video clips.

Table 4

*Instances of Content and Media types contributed by students and teacher in PLACE.web*

<table>
<thead>
<tr>
<th>Content Type</th>
<th>Real-World Examples</th>
<th>Lab Reports</th>
<th>Multiple-Choice Homework Problems</th>
<th>Culminating Activity Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instances</td>
<td>120</td>
<td>56</td>
<td>36</td>
<td>31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Media Type</th>
<th>Image</th>
<th>Embedded YouTube clip</th>
<th>Personally Recorded Video</th>
<th>Personal Narrative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instances</td>
<td>61</td>
<td>48</td>
<td>55</td>
<td>10</td>
</tr>
</tbody>
</table>

4. **Encouraging students to engage with a broad range of principles.**

An examination of individual students’ tagging of principles across all the submitted examples shows that, on average, each student tagged at least one example with 10.3 of the possible 14 principles (Figure 21). It is important to note that these are only the principles the students tagged themselves, and doesn’t include the principles they voted on. When including voting on principles, students on average engaged with 13.6 of the 14 principles, with 70% of the students
engaging with all 14. This shows that students were able to directly engage with most of the major principles in the curriculum and connect them with their everyday lives – one of the central goals of the curriculum for our co-design teacher.

Exit interviews further support PLACE’s ability to make the connection between classroom physics and the everyday lives of students:

*I think that really made us think and made us also realize that there really is physics in everything, because once we got talking with friends to figure out where can I find Newton’s First Law, or Second Law, or Third Law, it was really in literally every aspect of our lives… it really made us see that what we learned in class actually applies to things outside or class, in our regular in our everyday life.* (Rebecca)

It was very interesting because we applied our knowledge and I feel that’s something that other classrooms really don’t get to nowadays, it’s knowledge and raw concepts. But when you bring things from outside into [PLACE.web], like examples, you really get to connect your
knowledge… It definitely [helped] me to understand physics concepts better and generally understand how the world works. (Sam)

The analysis above supports the notion that S3 can facilitate students’ construction of a knowledge base that is indexed to a broad range of domain principles, and distributed across multiple content areas (in this case the three curricular units) and a wide range of media types. In the next section I examine how students used S3 to contribute to the knowledge base, how it facilitated the sharing of ideas and collaboration, and facilitated student contributions across multiple learning contexts.

5.3 Analysis of KCI Principle #2: The knowledge base is accessible for use as a resource as well as for editing and improvement by all members.

5.3.1 S3 design: Supporting KCI Principle #2.

In order to support this principle, we needed to ensure that the knowledge base was easily accessible, editable, and flexible for a variety of inquiry applications in PLACE. This means that our curricular designs would require flexibility in the kinds of artifacts that students could contribute to the database, and allow students to make unforeseen connections between them (through social or system generated semantic structures). The NoSQL approach described above (Section 5.2.1) is particularly well suited for data that is “unstructured” (does not fit into neat column and row tables), such as notes, images, and video (Leavitt, 2010), with emergent characteristics such as social information (tags, votes) or links and emergent structure.
Another important requirement or implication of this KCI principle is the need for querying and comparing individual and whole class contributions to the knowledge base in order to make recommendations of artifacts or even student groupings (i.e., based on expressed interests or patterns of contribution) that may be relevant to the inquiry design. In response, we developed a real-time messaging system that employed a combination of XMPP (Extensible Messaging and Presence Protocol) and a Pub/Sub (publication and subscription) model, allowing individual services, software agents, and devices to “subscribe” to specific event notifications (e.g., to be notified whenever a specific artifact been updated). For instance, if a student replies to a note, a software agent that is “tracking” that note can notify the original author that a change has been made. This notification might encourage the original student author to re-visit the note and add to the evolving discourse. This approach also allowed us to consider more global notifications; for instance, students could be tagged as “experts” (either intentionally by the teacher, the student him/herself, or by the system by tracking past actions) and the S3 notification system could inform them when new items are tagged with their expertise. In this way, S3 could support new ways of connecting students to relevant materials and help them make sense of large and growing data sets – a significant challenge in supporting complex inquiry.

An important commitment of KCI, in regard to making knowledge accessible is concerned with the construction of aggregate visualizations of student contributions, presented in large, dynamic displays, as well as on students’ personal devices. These knowledge representations serve to support individual students, dyads, and small groups in their inquiry activities, as well as whole class engagements and teacher orchestration. In our preliminary designs (e.g., those described in Chapter 3), many of these aggregates were designed with a combination of HTML 5 and Flash.
However, because Flash has become increasingly ill-supported on tablets and mobile devices, the current version of S3 employs D3.js, a JavaScript visualization library that has gained popularity for its ability to customize the visualization of database queries, allowing for their direct manipulation (e.g., dragging, filtering, or resizing) by end-users (students and teachers). D3.js was a great match with the real-time messaging protocol of S3, as it would allow us to update the visualizations in real-time, letting students to see their contributions to the knowledge base as they occurred.

5.3.2 S3 implementation: How PLACE supported KCI Principle #2.

Using the S3 messaging protocol, we added newsfeeds to the individual student homepages in PLACE.web, notifying students when personally relevant items in the knowledge base were changed or assigned by the teacher. This allowed students to track their own progress and provided them with avenues for (re-)engaging with the community knowledge base. Although not implemented during this iteration of PLACE, the ability of S3 agents to know and track individual student learning traces and areas of expertise, offers the potential for recommending new areas of the knowledge base (or peers’ contributions) that may be of interest to him or her (similar to popular “recommender” systems on sites like Netflix).

During the culminating activity, PLACE.neo allowed students to move objects from their personal devices to shared interactive displays to support the collaborative negotiation of ideas. Through each stage of the activity, the negotiated objects (e.g., a collection of negotiated equations) were persistently shown on each zone’s display (using D3.js) giving the entire class insight into the growth ideas at each zone. These large-format aggregates also served as a means
for the teacher to engage with individual groups on idea refinement and possible next steps in their inquiry.

5.3.3 S3 evaluation: Supporting KCI Principle #2.

In evaluating the S3 PLACE implementation, in terms of its support for KCI Principle #2, three features can guide our analysis: 1) Student engagement with the knowledge base; 2) Inter-student activity (i.e., how often did students interact with their peers and how many different students did they interact with); and 3) Support for ubiquitous access to the knowledge base.

1. Student engagement with the knowledge base.

Figure 22: Individual student contributions to the PLACE.web knowledge base. Note: Student SPH03-17 is not included because he switched classes shortly into the curriculum.
Between the two classes, students contributed 120 examples, 56 lab reports, and 13 challenge problems to the knowledge base. Between the examples and the lab reports, students contributed 635 discussion notes (~3.6 notes/example). Students attached a total of 1066 principle tags to these contributions, and cast 2641 votes of the assigned tags. Figure 22 shows the frequency of individual student contributions to the knowledge base for one of the two physics classes. This level of activity supports the interpretation that students were able to engage with the knowledge base.

2. Inter-student activity

One of the main goals of a KCI curriculum is for students to build on the ideas of their peers and to work collectively as a community in the generation of ideas. In order to evaluate how effective PLACE.web was at supporting students in connecting with their peers, we examined the server logs to see how many different members in the community they (a) engaged in discussion with on a peer-contributed artifact, and (b) both voted on the principle which attached to an example (Figure 23). In terms of the part (b), they did not have to vote the same (up or down), they only...
had to have both voted on the same item. Across both classes students engaged with 95% of their peers in some capacity, showing a high level of inter-student activity.

During the culminating activity, we wanted to see how many of their peers students worked with, to get a sense of how well PLACE.neo supported opportunities for collaboration and fostered a “collective epistemology”. Across the four PLACE.neo runs, students collaborated with, on average, 62% of their peers directly (i.e., in synchronous collective or collaborative tasks). When looking at students working with the ideas of their peers, across all four PLACE.neo run, every student engaged with, built on, or debated at least one contribution from every other student in the class. Fostering an environment in which students engage with the ideas of the entire community is a particularly difficult thing to achieve in collective inquiry, but one that was ideally suited for the S3 framework. Aggregating individual student work on the large collaborative displays provided a clear visual space for small group discourse and negotiation. In exit interviews with the students, they noted that having the information of their peers available on the large format displays made it easy to see and discuss with their group members.

Just looking at what other groups had left us you got a good sense, and then from there the group could take over and be like this is what we need to do to solve it. (Dilpreet)

Students remarked that, compared to traditional laptop screens, the large format displays encouraged more involvement between peers, and overall engagement with the activity.

You were definitely more willing or open to discussing the ideas and going back and forth on things. (Pearl)
In class if a teacher were to tell [a group] to solve a problem together then [laughs] I would say that rarely everyone participates, and there are one or two people who are just not doing anything, but in here it really engaged us to participate. (Rebecca)

Students also remarked that the S3 framework helped them to both gain insight into, and build off the ideas of their peers.

_You could submit your answers on the tablet and you’d see like what your friends were doing and see if your group agreed with you, and I thought that was really good, because you could not only depend on your own opinions but also the other perspectives._ (Christine)

The above analysis shows how S3 was successful in connecting students with the work of their peers and in supporting collaboration, negotiation, and engagement as a community.

3. Support for ubiquitous access to the knowledge base.

![PLACE.Web Contributions: Total contributions by time of day](image)

_Figure 24: Total number of student contributions to PLACE.web by time of day. The distribution shows that students contributed to the knowledge base at every time of the day, other than during the period of time between 3am – 6am._
Throughout the PLACE curriculum, students were actively engaged with the knowledge base in school, at home, and in their neighbourhoods. An examination of the time of day that students contributed to the knowledge base (Figure 24) shows that students uploaded content or contributed comments and rationales at almost every point in the day (the exception being between 3am and 6am). This highlights PLACE.web’s ability to support students across contexts, with 53.42% of the contributions taking place outside of school hours (4pm-9am). Interestingly, about 2% of the contributions took place during lunch hours (12:30pm-1:15pm), indicating student interest in the PLACE content even when outside normal class periods, but still in the formal school setting. The teacher involved in the study noted that students came up to him in the hall with their mobile devices, to bring up a homework question or a peer’s example, and asked his thoughts about their response. He stated that he was amazed not only at their interest, but also their ability to have the content “at their fingertips”.

The three points above show how S3 was successful in supporting students as they engaged in a sustained knowledge community in which their activities, knowledge building, and collaboration were distributed across multiple learning contexts and scales of time. During the culminating smart classroom activity in particular, S3’s large collaborative displays were effective in not only making the ideas of the community visible, but also in supporting group discussion.

5.4 Analysis of KCI Principle #3: Collaborative Inquiry activities are designed to address the targeted domain learning goals, using the knowledge base as a primary resource and producing assessable outcomes.

5.4.1 S3 development: Supporting KCI Principle #3.
Within a DTEL environment, there is an ever present challenge in coordinating and delivering structured materials, tools, simulations, and visualizations directly to students depending on their present context or assigned task. We felt that our vision of a real-time messaging system within S3 could help support this connection between students, their devices, and context specific materials and scaffolds. We wanted to be able to support students in making social and collaborative connections by reflecting their actions (e.g., class tagging, voting or sorting of ideas) in real-time, either on their individual devices or on aggregated displays (e.g., large-format displays).

It was also important that the DTEL environment be able to leverage system- or teacher-generated metadata to organize students in *ad hoc* groups (short term collaborations), as it would allow us to investigate more complex student configurations and collaborations based on both pre-defined (e.g., jigsaws based on student expertise) and emergent conditions (e.g., patterns of student tagging or artifacts). We felt the use of a NoSQL database, which allows for the easy creation of new metadata (e.g., group or expertise assignments), coupled with a robust real-time data mining and messaging system, would allow us to investigate how such configurations could play out during both synchronous and asynchronous activities.

Within groups, we also needed to be able to further contextualize the information, tasks and materials sent to students and allow for real-time communication and idea sharing (e.g., group focused chats or discussions, or document sharing and editing similar to Google Docs). Using a NoSQL approach for the assignment of metadata concerning group configurations meant that we could assign roles, goals, tasks, and materials uniquely to each student in a group and each group in the class.
Because of the cross-context nature of our design, we needed S3 to support a wide range of individual and collaborative activities that allowed students to contribute to, access, and edit the knowledge base. This required us to develop the S3 messaging protocol and database to allow for the use of JavaScript, HTML5, and native operating systems (iOS and Android), to allow us to leverage each one’s unique affordances for rapid design, visualization of data, and human computer interaction. We wanted students to be able to capture probe data on an iPhone, engage in discussion on observed results on their laptops at home, and collectively vote on next steps using their Android tablets in class. In order to facilitate the cross-platform exchange of information we developed “Drowsy Dromedary,” a RESTful API that is device agnostic, allowing any device to generate customized queries from the S3 database. By placing the burden for deciding how objects are retrieved, aggregated, visualized, and edited on each individual device, we could allow for greater flexibility in how the objects are used on a device-by-device basis.

A similar challenge was how to support students’ information searching practices within a growing knowledge community. We understood that making this information available to students, in ways that were meaningful and useful in supporting their inquiry as a community, was a significant challenge. As part of its development, we wanted to investigate how the underlying data structures and messaging protocols within S3 could provide new ways of addressing these challenges. In response, we felt that developing aggregated visualizations using D3.js could provide us with the opportunity to investigate how to represent the growth of student ideas over the course of a persistent curriculum.
One of the cornerstones of our design was the need for S3 to support real-time pedagogical logic that allowed consequential scripting moves to be performed during inquiry activities. A central challenge in developing such support was that much of the required information required to enact this logic could not be known a priori. Rather, it would only emerge during the activities, as a consequence of ill-determined student interactions. Such logic could include the re-forming of groups based on emergent class patterns, or the distribution of materials (including individually, whole class, and within and across groups).

The use of intelligent software agents offers considerable promise for such logic support. For instance, a Bucket Agent may be tasked with distributing materials from the knowledge base among group members that match tags generated during a brainstorming session. Although the agent might know the condition it needs to satisfy (e.g., provide group members with all the objects in the database that are share the same metadata as their brainstorming document), it cannot know beforehand what tags students will gravitate towards and therefore which objects it will need to pull and distribute to the group. The design of these agents is particularly powerful for emergent learning environments, as they can be designed beforehand and enacted when needed in the script automatically, freeing the teacher to focus on supporting student learning.

5.4.2 S3 implementation: How PLACE supported KCI Principle #3.

In PLACE.web, as students contributed tagged items to the knowledge base, using D3.js, S3 was able to visualize the growth of student ideas in as a filterable web of semantically connected concepts, named the Associative Web (Figure 25). This made it possible for students to view the knowledge base as a collective knowledge resource (rather than a diaspora of ideas), and to find resources that fit their own areas of expertise, for commenting, critique, and
refinement. Allowing students to customize their view of the knowledge base to suit their inquiry practices (i.e., by filtering the web based on specific principles, range of date, type of contribution, or to only show items they had contributed to) was an important factor in helping manage the flow of information as the knowledge base grew.

Throughout the enactment of PLACE, S3 played a vital role in facilitating student use of the knowledge base across multiple contexts and use-cases. During the at-home pre-activity of the culminating PLACE script, students were tasked with individually tagging with principles and equations to a set of physics problems. Because we didn’t need every student to see every problem (only requiring that all the problems get covered by “enough” of the students), we could use S3 to coordinate the delivery of the problems to the students at home. In this case each
student was assigned a specific sub-set of the overall problems, with enough overlap to ensure that each one was addressed, even if not every student completed the homework (a persistent challenge in any classroom!).

During the in-class portion of the culminating activity, when students formed consensus on the principles and equations, S3 was able to aggregate the individual homework responses to give each group an overview of the whole class’ thinking to help them reach consensus. Similar to our earlier studies, these aggregates allowed the students to build off the contributions of their peers; however, unlike in the earlier iterations, the task didn’t revolve around solving the problems (which “gave too much away”), instead focusing on the supporting characteristics (i.e., the principles and equations).

In the smart classroom portion of the culminating activity, students used the work of their peers, which was filtered and provided to them by S3 data mining and intelligent agents, to help scaffold their problem solving. S3 agents played an important role in coordinating the flow of activities and students within the room. Based on emergent class patterns at each zone (such as the number of tags submitted by individual students), S3 agents were able to make decisions of where students should be moved throughout the room and whom they should be grouped with (described in detail in Principle #4 below). Once formed, S3 Bucket Agents would send scaffolded materials to members of the group based on each zone’s uniquely negotiated metadata (e.g., the problems from the pre-activity assigned to the board).

5.4.3 S3 evaluation: Supporting KCI Principle #3.
In supporting KCI principle #3, we evaluated the S3 PLACE implementation along three distinct features: 1) How did the PLACE S3 implementation facilitate the reuse of student-contributed materials to support their inquiry activities? 2) How did the S3 framework support students in producing assessable outcomes, especially within the DTEL environment? 3) What level of fluency did students show in constructing their final artifacts within the DTEL environment?

1. Facilitating reuse of student-contributed materials to support inquiry activities.

![Figure 26: Student negotiated Equations and Variables and Assumptions (VA) available to students on the co-constructed interactive display, and their use in student generated final answers](image-url)
The “challenge problem” script successfully engaged students in leveraging the collective knowledge base towards developing new objects for peer engagement and investigation. In total, 13 challenge problems were developed, with each problem referring to on average 2.23 examples from the knowledge base. The Associative Web employed the underlying S3 data mining structures to support students in the activity, helping them find examples that matched their expertise groups and supported their creation of challenge problems. Post-interviews indicated that students found the Associative Web very useful for filtering the overall knowledge base and finding artifacts that matched their search criteria. One student noted that it “made it clear what examples are related to our concepts, because you could see what example was related to more than one of the concepts, and it's easy to browse through multiple areas.” (Dilpreet)

During the culminating activity, the S3 framework was successful in providing students objects from the knowledge base to support their inquiry needs. The S3 agents played a particularly important role in this regard, by responding to emergent student actions (i.e., actions that were not known or knowable beforehand), to supply groups semantic and task relevant artifacts from the community knowledge. During Step 2, the Bucket Agent supplied each group with problems whose principles matched those that had been negotiated by students for their scenario. The agents connected, on average, 23 problems to each scenario, distributed evenly across all group members, who then promoted 3.4 problems on average; these were negotiated down to 2.6 on average. During Step 3 (“Equation Assignment”), the Bucket Agent drew equations from the knowledge base that had been previously tagged (in a pre-activity) to the negotiated problems, to serve as a further resource for students. From these agent-filtered equations, students
recommended an average of 4.9 equations, which were negotiated down to an average of 4.3 (Figure 26).

2. Supporting students in producing assessable outcomes

When comparing the groups’ final answer sheets with their co-developed evidence on the large-format displays (Figure 27) we found, on average, groups used 54.6% of the assigned equations and 76.8% of the assigned variables and assumption (Figure 10 above). We were curious why (especially when compared to variable and equations) the percentage of equations was so low. Exit interviews indicated students preferred to keep more equations on hand (in their tool belt) until they were sure which they would use.

*If we were not totally sure like it’s a grey area... we would just put it in “yes” just in case.* (Sarah)

*Figure 27: This shows a group’s final worksheet for solving their challenge problem. The red boxes highlight which elements (i.e., equations, variables, and assumptions) on the worksheet correspond to the co-developed elements from their zone’s interactive collaborative display.*
3. Student fluency in constructing their final artifacts within the DTEL environment

In order to evaluate students’ physics fluency during the culminating activity, several elements of the problem solving process were examined. First, because the fourteen principles were a major focus of the curriculum, we compared the accuracy of the individually submitted principles from Step 1 and the final group negotiated set, to an expert classification done by the teacher for each zone. Across all four zones, the groups outperformed students working individually (See Figure 28). When comparing all the zones collectively, there was marginal significance (individual Mean = 62.91%, group Mean 75.01%), with $F(1, 30) = 3.140, p = 0.086$. These findings are consistent with our earlier design studies (Lui, Tissenbaum & Slotta, 2011), in which groups outperformed individuals in assigning principle tags to examples of physics.

![Figure 28: Accuracy percentage scores for individual and group tagging of physics principles during the culminating smart classroom activity. Across all four zones, the groups outperformed the students working as individuals.](image)

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In order to evaluate the quality of the assumptions and variables created by each group for their zone’s scenario (in Step 3 of the culminating activity), the teacher evaluated each group’s final negotiated set using a four-point scale that rated them based on their completeness for solving the problem (Table 5). Across the four sections, the students scored an average of 2.6 (with no groups scoring below a 2), indicating a high ability to identify the elements of an ill-structured problem.

Part of the reason for the high score may be attributed to the condition that the teacher was prompted (on his orchestration tablet) to review and approve each group’s variables and assumptions prior to them progressing to the final problem solving stage in the activity. In order to assess this possible effect, the groups’ set of variables and assumption was scored before the teacher asked them to revise their work and after. In total, across the seven resubmissions, the groups added seven new variables and assumptions. These resubmissions resulted in an average change of 0.58 in their assessed score, indicating that the teacher’s intervention has a meaningful effect on the groups’ variable and assumption construction (Figure 29 below).

Table 5

*Rubric for scoring group assumption and variable construction during Step 3 of the culminating activity*

<table>
<thead>
<tr>
<th>Score</th>
<th>Level</th>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No correct assumptions or variables • The group failed to provide any assumptions or variables that could be used to solve the video</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>One assumption or Variable • The group were able to successfully identify at least one variable or assumption that they needed to solve the video</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Incomplete set • The group was able to assign several assumptions and variables to the video but did not identify all of them</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Complete Set • The group successfully provided all of the necessary assumptions and variables needed to solve the video</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The group’s final video recorded answers and answer sheets were evaluated together by the teacher using a Knowledge Integration (KI) scale, which scored students on the depth and quality of their answers and their connection to valid physics concepts on a scale from 0 to 5 (Table 6; Linn & Eylon, 2011). Overall, the students scored very high, with an average KI score of 4.5, indicating a high level of understanding and integration of the physics in the video problems. This was especially encouraging given that for one video in particular (Video D) students struggled significantly more than in the others (Mean 3.75).

![Figure 29: Variable and Assumption scores for groups before and after the teacher requested the group go over their negotiated set again (Note in the case of Day 1, Zone B, the score was already 3/3 and no additional elements were added which may indicate that the teacher simply asked them to think about it some more, but they did not have to make any changes. On Day 3, Zone B, the group did add another element that was considered significant by the teacher, but they still missed one preventing them from achieving a perfect score).](image)

Table 6

Student KI scores for the final video recorded answers
<table>
<thead>
<tr>
<th>Score</th>
<th>KI Level</th>
<th>Description</th>
</tr>
</thead>
</table>
| 0     | No solution | - The recording was not connected to the assigned problem  
        |          | - The answer did not address the assigned problem |
| 1     | Off topic | - Showed a basic understanding of the problem needed to be addressed  
        |          | - Some attempt was made to solve the problem, but no solution is presented |
| 2     | Minimal | - Showed a competent understanding of the problem and concepts presented, but had a limited and wrong answer  
        |          | - Full answer (not necessarily correct), but showed only limited understanding of the problem and concepts presented |
| 3     | Limited | - Showed a full understanding of the problem but has some inaccuracies or gaps in their solution  
        |          | - Provided a complete solution but shows some gaps in understanding of the concepts at play |
| 4     | Partial | - Showed complete understanding of the problem and provided a complete and accurate solution |

Overall, this analysis shows S3 was successful in supporting students in both accessing and reusing the community’s knowledge in pursuit of targeted learning goals. The scores based on the rubric for the constructed assumptions and variables and the knowledge integration (KI) of the groups’ final products are an important cue to the efficacy of S3 to support students in these activities, as they illustrate its ability to connect students with the necessary materials and tools to complete their tasks.

5.5 Analysis of KCI Principle #4: The teacher plays a critical role in orchestrating the pedagogical script and adapting its execution in response to emergent ideas and avenues of inquiry
The challenges of defining and then supporting the teacher’s role are common to many collaborative inquiry approaches. In general, it is challenging for teachers to engage in such pedagogy, which requires them to be particularly attentive to specifics of student work, collaboration, and the progress of the classroom as a whole. Because the challenges of orchestrating complex collaborative inquiry are somewhat general to PLACE and other projects, and substantive literature in the field has highlighted orchestration as a major challenge in the successful orchestration of knowledge communities (Whitcomb, 2004; Wang, 2009; Sutherland, Rosamund, et al., 2004), this section can be seen as an attempt to support orchestration more generally (above and beyond supporting KCI Principle #4).

### 5.5.1 S3 Development: Supporting KCI Principle #4.

The distributed nature of a DTEL environment meant that we needed to develop a system in which we could coordinate and update all of the devices simultaneously, rather than manually or individually. We conjectured that making it possible for any device or service to subscribe to a specific event notification, would allow for a single message in S3 to affect multiple devices in the room simultaneously – tablets could bring up new instructions, interactive screens could show new phenomena or representations of class knowledge, and agents could be launched to provide additional orchestrational support (such as forming groups). We didn’t want every moment in the script to be hard coded, so we also needed students to be able to move through several tasks at their own pace within larger “block of activities”, receiving pertinent information, materials, and prompts as necessary (rather than as a whole class). Developing a framework that allowed for the individualization of device subscriptions, notifications, and
updates meant we could design for a wide range of orchestrational granularity and configurations.

In developing S3, we wanted to investigate an expanded role for intelligent software agents to support the teacher in orchestrating class activities. We knew from our previous designs (described in Chapter 3) that agents could assist the teacher by offloading many of the procedural aspects of the class management (e.g., the distribution of materials to individual students or groups). The use of the real-time messaging system and Pub/Sub model in S3 meant that we could now have agents listen to a wider range of events, and make more complex decisions based on emergent class patterns than in previous designs. For instance, when an event’s state changed (e.g., a group’s negotiation state is changed to completed), an agent subscribed to that event can execute predefined pedagogical logic in response (e.g., notify the teacher to review the students work). This allowed multiple agents to subscribe to the same event or to update multiple devices – in the example above the agent could notify the teacher that the task is done, but it could also update an ambient or aggregate display, and at the same time update each group member’s tablet with new items or instructions. In order to understand the impact that an expanded role for agents could have in a DTEL environment, we wanted to look at how four agents in particular might help in orchestrating class activities (Table 7): 1) Student Sorting Agent; 2) Consensus Agent; 3) Bucket Agent (partially described in Principle #3 above); and 4) Student Progress Agent.

Table 7

S3 Intelligent Agent types and descriptions
In order to ensure that the teacher had a meaningful role in the community, we wanted to make certain that the script included a significant level of orchestrational control for the teacher over the progression of activities. Applying the S3 messaging protocol allows for the support of a range of dedicated orchestrational technologies, including teacher orchestration tablets and various forms of ambient displays. By centralizing the control of the room, the teacher could move the class through stages of the activity, change representations or phenomena, or alter group configurations from a single device, rather than having to move throughout the room.

<table>
<thead>
<tr>
<th>Agent Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student Sorting Agent</td>
<td>• Sorts students both into groups and around the room</td>
</tr>
<tr>
<td></td>
<td>• Sorts can be designed in two ways:</td>
</tr>
<tr>
<td></td>
<td>o Pre-set by the instructor or researcher</td>
</tr>
<tr>
<td></td>
<td>o Emergent based on individual, small group, or whole class actions</td>
</tr>
<tr>
<td>Consensus Agent</td>
<td>• Monitors groups of students where activities required achieving consensus</td>
</tr>
<tr>
<td></td>
<td>o Students cannot move to the next step until consensus is achieved</td>
</tr>
<tr>
<td></td>
<td>• Also used as an orchestration tool to alert teacher to review student</td>
</tr>
<tr>
<td></td>
<td>consensus when necessary</td>
</tr>
<tr>
<td>Bucket Agent</td>
<td>• Coordinated the distribution of materials to students in two possible</td>
</tr>
<tr>
<td></td>
<td>ways:</td>
</tr>
<tr>
<td></td>
<td>o Ensured that all members within a group had an equal but unique subset</td>
</tr>
<tr>
<td></td>
<td>of materials from a given set (i.e. a series or problems or equations)</td>
</tr>
<tr>
<td></td>
<td>or</td>
</tr>
<tr>
<td></td>
<td>o Distributed materials to all members to ensure that all members</td>
</tr>
<tr>
<td></td>
<td>completed a task at the same time (quicker students may receive more</td>
</tr>
<tr>
<td></td>
<td>items to work on than slower students)</td>
</tr>
<tr>
<td>Student Progress Agent</td>
<td>• Tracks individual, small group, and whole class progress</td>
</tr>
<tr>
<td></td>
<td>• Sends updates to other devices (i.e. ambient display, teacher tablet)</td>
</tr>
<tr>
<td></td>
<td>o Can aid both teacher and students in knowing if students are</td>
</tr>
<tr>
<td></td>
<td>falling behind the rest of the class</td>
</tr>
<tr>
<td></td>
<td>• Coordinates the timing and delivery of materials</td>
</tr>
</tbody>
</table>
making sure each student or group is properly setup. The real-time messaging protocol could also allow the teacher inject new items (e.g., new multiple-choice problems, student polls, or tags) into the flow of activities. Once a new item was added, the necessary devices (e.g., individual student tablets, or collaborative displays) could be instantly updated to reflect the change in the script.

Building on our initial design studies, we realized that providing the teacher with timely and context sensitive information was critical in order to effectively support him or her in monitoring student progress and making on-the-fly orchestral decisions. The combination of the event subscription model and intelligent agents in S3 could allow the room to track procedural information, such as which activity each student (or group) is currently working on, and when they started or completed a task. In this way, when specific events are triggered (e.g., a group completes a tagging activity), an agent can alert other devices (e.g., the teacher’s tablet or an ambient display), updating their representations or triggering a new event.

We also needed to address the issue identified within our initial design studies, of limiting the amount of time the teacher has to be “heads down” on his tablet. To this end, we aimed to advance the notion of “ambient displays” - large vertically mounted screens which the whole class could see “at-a-glance”. These displays could show persistent (and often changing) information that is important to the orchestration of class activities (e.g., the location of students in the room, the timing of activities, rolling newsfeeds of generated content), but does not need to be presented at the center of the class’ attention. The real-time messaging and intelligent agent architectures of S3 could allow these displays to be updated as actions occur, providing immediate updates during live activities. For instance, as a Sorting Agent places students in
groups, it can send a message to the ambient display showing students where to go in the room. During longer designs, spanning multiple classes, the ambient displays can be used as a means of showing community updates (such as changes to the knowledge base) that may have happened between class periods (e.g., by students at home).

When designing PLACE, in addition to having student work aggregated on large community displays, we also considered how the distribution of students within the physical space supported individual, small group, and whole class inquiry. From our earlier research, we also understood that both these features are instrumental in supporting the teacher’s role within the community. Similar to successful Problem-Based Learning (PBL) approaches (Hmelo-Silver, 2004) with post-it boards, we understood that the use of large displays spread throughout a DTEL environment can give the teacher insight into the immediate work of distributed groups of students, as a means for helping him decide where he is most needed (operating as a “wandering facilitator”). We also understood from our earlier studies, that these larger displays were more useful (than the smaller tablet screens or laptop screens) as a way for the teacher to engage with the students around their ideas.

At the completion of a knowledge building activity, the large central displays can be used to engage the whole class in discussion around the generated ideas, highlighting any emergent community trends or to help guide subsequent activities. Because we designed the large-format displays in S3 (using D3.js and HTML5) to allow for the manipulation, filtering, and editing of the displayed aggregated knowledge, we felt we could provide the teacher with a wide range of approaches to orient class discussions.
Building off of our previous designs, we also knew that it was important to provide the teacher with generated reports of student contributions, and other analytic functions, both inside and outside of class, in order for him to be able to reflect on the overall state of the community’s knowledge and individual students’ progress, to help inform upcoming class activities. The use of the NoSQL database gave us significant leeway in the design and development of these reports, and further supported our design-based approach to the development of S3. During the intervention, if the teacher required new forms of assessment or report generation, it would be easy to create new relationships between objects in the database (by simply generating new Key-Value pairs), without needing to worry about rebuilding the whole database (a common challenge in traditional SQL databases).

5.5.2 S3 implementation: How PLACE supported KCI Principle 4

**Script Authoring and Execution**

As part of the PLACE.web portion of the curriculum, the teacher was able to review student-contributed artifacts in the database using both a structured list of all the contributed items and through the associative web. This allowed him to find objects specifically tagged to principles currently being covered in class. The teacher was also provided with an assessment tool through which he could individually score student contributions (on a scale of one to four). The combination of these two features provided the teacher multiple lenses from which to view the overall state of the class’ knowledge, in order to make decisions about what topics or issues to cover in upcoming classes.
To support the teacher in introducing new items into the script, such as homework problems, we developed a specialized teacher-authoring portal. This portal allowed the teacher to create an artifact, including multi-media elements and text, and pre-tag it with principles. We also created a specific newsfeed for teacher-introduced items on each student’s home page. The teacher’s own home screen was updated each time a student completed an item he had assigned, informing him which student it was and providing a link to the student’s work for the purposes of assessment.

During the smart classroom activity, S3 was instrumental in supporting the teacher. The real-time messaging in PLACE.neo allowed us to scaffold student interactions in real time, and gave the teacher a clearly defined orchestral role in progressing class activities. The development of the teacher orchestration tablet (Figure 30), allowed the teacher to control the class’ progression through the activity. Although students were free to progress through several micro-stages within each step of the activity at their own pace, at critical moments (such as when students were re-grouped) the
teacher was able to launch tasks simultaneously on every device in the room.

**S3 Intelligent Agent Architecture**

The S3 agent architecture was used extensively in PLACE.neo to help coordinate the flow of materials and students during both the pre- and smart classroom activities. Below, I describe each of the agents designed for this activity in detail in terms of their specific orchestrational roles in the PLACE.neo.

The *Sorting Agents* were used at two key moments in the smart classroom script. The first happened between Step 1 and Step 2, where we wanted students to be grouped based on the frequency of their tagging of each video (placing them at the board where they had submitted the most tags). For this condition, the *Sorting Agent* needed to know how many principles each student had submitted to each video and cross-reference it to every other student in the class. Since we could not know which tags students would assign to each video, this meant there was no way for us to know where the students would be sorted beforehand. Similarly, between Step 2 and Step 3, we wanted to group students with peers they hadn’t worked with previously (as a way of introducing them to new perspectives). In this case, the agents needed to keep a mapping of where students had been and when in order to make the groupings. The complexity of these conditional sorts, based on emergent patterns, would be procedurally impossible for a teacher to do, even between classes let alone in real-time. Supported by the S3 agent architecture, the teacher was able to enact these sorts instantly, with a single press on his tablet.

The *Consensus Agent* was used in both the in-class and smart classroom activities in order to help monitor and coordinate task completion. During the pre-activity, the agent ensured that
every group member had the same principle and equation tags chosen for a problem before allowing them to submit their group’s answer. During the smart classroom activity, the Consensus Agent required students to make a decision on all of their individually submitted elements (e.g., equations or variables), by dragging them to either the “Yes” or “No” space on their group’s interactive display, before allowing them to press “submit”. In both cases, this freed the teacher from having to make sure each group had completed the task, instead focusing on talking with students about their ideas.

In the in-class pre-activity, a Bucket Agent was used to distribute problems to the groups so that as soon as any group completed a problem, the agent sent them a new problem. As groups completed their problems, the agents provided them with a new one until all the problems in the “bucket” had been distributed. This was done to ensure that all the problems were covered in the allotted time, by giving students who were working slower less problems, and those who were progressing fast more. This contrasts the use of the Bucket Agent during the smart classroom activity, which aimed to evenly distribute semantically relevant materials from the database to promote group collaboration.

In PLACE.neo, Progress Tracking Agents were used to inform the teacher whenever a group completed an activity. For instance, when the “tag negotiation completed” message was sent out by a group’s collaborative interactive display, the agent notified the teacher’s own tablet, which updated to show this change. In most cases within PLACE.neo, the teacher was not required to act on this information, rather it was provided to as a means of letting him know if a group was falling behind, or when all the groups had finished a step (letting him know that the whole class was ready to progress to the next step).
In Step 4 of the smart classroom activity, we wanted the teacher to explicitly intervene at a critical moment in the script: after a group had come up with a set of assumptions and variables for solving their problem. Once a group had reached consensus on the assumptions and variables, an event trigger was sent via an S3 Progress Agent. The teacher’s tablet, listening for the event, lit up informing him he needed to visit that group and either approve their work or have them work on it some more. By using the underlying agent infrastructure and messaging protocol in S3, the orchestrational load placed on the teacher to know (at least on some level) when and where he was needed was reduced by his awareness that he would be alerted on his tablet. This allowed the teacher to more freely roam the room engaging with students based on group needs.

**Ambient Displays**

Ambient displays had several important roles in helping orchestrate the classroom in PLACE.neo (Figure 31). When the teacher launched a particular task, such as having the student initially tag a video, the messaging system alerted the Ambient Display that the task had begun, triggering the display’s task timer. This timer displayed a coloured bar at the top of the display, which began as...
solid green, but started to flash with increasing frequency, changing in colour to yellow and then red, and finally greying out the screen with the phrase “Time’s up!” when the activity timed out.

Placing this information clearly at the periphery of the class’ attention removed the need for the teacher to constantly check his watch, while simultaneously helping the students self-monitor the timing of their task progression. The ambient display also tracked students in the room by displaying personal avatars mapped to their current location. During the agent administered sorting of students after Step 1 and Step 2 (see above), the Ambient Display showed students their new locations in the room by animating the movement of the individual students to their new locations – giving the class a clear visual cue of where they needed to go next. As students completed tasks, a Progress Agent would send a message to the ambient display, and the display would light up showing a “task completed” animation and an activity icon would appear next to the student’s avatar. By making the task completion explicit and viewable by all members of the community, we hoped to encourage self-monitoring and task regulation among students, thus reducing the load on the teacher.

**Large-Format Collaborative Displays**

The large-format collaborative displays, which showed the collective work at each zone in the room, helped the teacher decide where he was needed at-a-glance, and engaged the individual groups in discussion around their co-constructed ideas. By making the work easily seen by the teacher, instead of being obscured by laptop lids (Sharples, 2013), we were able to support the teacher as a “wandering facilitator” and active collaborator, rather than as a passive guide at the edges of the student work.
5.5.3 S3 evaluation: Supporting KCI Principle 4.

In order to understand the role S3 played in supporting Principle #4 and the general orchestration of class activities, we can evaluate the enactment along four lines: 1) How did S3 support the teacher in engaging with the knowledge community? 2) How did S3 support the teacher in enacting specific pedagogical scripts and making necessary orchestrational moves to the script? 3) Did the S3 agent architecture successfully absorb a portion of the orchestrational load? 4) Did the PLACE DTEL environment help the teacher act as a “wandering facilitator” of class activities?

1. Supporting the teacher in engaging with the knowledge community.

During the PLACE curriculum, the teacher actively engaged with the students, both as a teacher and as a collaborative member of the knowledge community. In addition to the 36 homework problems (mentioned under Principle #1 above), the teacher also uploaded three examples to each class (six in total), and commented on examples uploaded by the students eleven times. Using the built in assessment feature of PLACE.web, the teacher made 257 individual assessments of student work in the community. Although the teacher contributed slightly less comments than the students on average (11 comments versus 17.5 on average), this is mitigated by the large number of assessments he made, which allowed him to engage with individual students directly. Overall these findings are encouraging, as they indicate that the teacher was able to interact with the community both as the “teacher” and more importantly as a co-collaborator in the knowledge community. In the exit interview, the teacher noted that the design of PLACE.web not only made it easy for him to engage with the students in ways that he felt
were more focused and personal compared to normal class activities, but also that doing so took very little time.

*Being able to enter a quick comment in there, is a different sort of feedback for the kids than getting a test back and looking at the marks and figuring out where comments were made. It’s an opportunity for a quick, little blob of feedback that a kid can get back on something specific, and normally they wouldn’t be able to get feedback on something quite so specific. For example I couldn’t give them even the slightest inclination of 1,2,3,4 [grade] for a typical homework question – it would only be general in-class broad stuff, but because they way we designed it, it really didn’t take that long to plow through a lot of these.* (Teacher)

Exit interviews with students support the view that the S3 environment was successful in integrating the teacher more as a member of the community than as the traditional “sage on a stage”.

*I felt like this was much better, because when you’re up in the [regular] classroom it’s more like the teacher is imposing their knowledge on you, while when you’re [in the DTEL environment] the teacher’s more of a guide, like a guiding instructor and the technology doesn’t really detract from the teacher’s job, but more just compliments it.* (Sam)

2. Enacting specific pedagogical scripts and making orchestrational moves.

In order to understand how the S3 framework supported the teacher in the real-time orchestration of the class, I conducted a video analysis of his actions in the smart classroom. All his orchestration “moves” were recorded (e.g. advancing the script, giving students feedback, and providing updates on the time left in an activity), and coded for any orchestrational
technology used during or just prior (such as looking at an Ambient Display – Table 8). The analysis revealed that the majority (81.25%) of the orchestrational moves made by the teacher were facilitated by an S3 orchestrational technology. This exhibits the efficacy of certain technologies to support specific orchestrational tasks over others, such as the teacher orchestration tablet for checking the status of individual students or groups, and the ambient display for confirming student locations in the room.

Table 8

*Frequency of teacher orchestration moves during two of the four runs and the “orchestrational technology” used to enact the move. Box colors indicate ranges of frequency (see legend below)*

<table>
<thead>
<tr>
<th>Teacher Orchestration Move</th>
<th>Check Status</th>
<th>Explain Task</th>
<th>Start Task</th>
<th>Check Timing</th>
<th>Check/Assign Location</th>
<th>Clarify Task</th>
<th>Approval Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teacher Tablet</td>
<td>11</td>
<td>4</td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Ambient Display</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>12</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Student Tablet</td>
<td>8</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Large Format Display</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>None</td>
<td>4</td>
<td>6</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

Legend:
- Green: 0-1.5
- Light green: 1.5-6
- Yellow: 6-10
- Orange: 10-15
- Red: 15-20
For instance, video analysis showed how the teacher’s orchestration tablet helped him know when all the groups had finished an activity (leveraging the *Student Progress Agents* in conjunction with S3’s real time messaging system). In each case, before progressing to the class to the next task, the teacher was observed checking his orchestration tablet to ensure that each group’s “task completed” icon was lit. In some cases the teacher double-checked the status of the students by asking if all the students saw the “cat” (an image on a wait screen between activities); however, this was only done during Step 1, where the status of individual students weren’t independently shown on the tablet (the tablet only showed when *all* the students at a board had clicked “complete”). This may be because the granularity of the feedback provided to the teacher didn’t match the granularity of the participants (students were working individually, but were shown as “groups” around the boards).

Exit interview questions, concerning the ambient display and its effect on student and teacher actions within the room, revealed some interesting responses. Several students mentioned that they found it useful at specific moments during the activity, but that the ambient display didn’t take up much of their attention.

*I thought it was a good way to see where everyone else was and to stay organized, I don’t remember worrying about it too much I was more focused about [our zone’s display], so it was nice but it wasn’t my main focus personally.* (Sarah)

Similarly the teacher noted that the ambient display was useful for to help him orient himself and the students to tasks and locations in the room, but that it also existed at the periphery of his attention.

*It was handy and it did work as a supporting technology feature that I’ve never experienced before... It certainly helped, I don’t think it was critical, but it was handy in those times, to let the kids know what group to get to, and it just resolved things*
quicker to get back to the physics of the moment... but I couldn’t really pay attention to it if I was embroiled in a particular group activity... so when I snapped out of it, then it was helpful to me. (Teacher)

The above quote is particularly telling in terms of the effectiveness of the ambient displays to support classroom orchestration, indicating the teacher’s acknowledgement of the display’s usefulness, without it requiring his constant attention. The ability of the ambient display to seamlessly support classroom orchestration is further supported by the contrast between the teacher’s statement above, that he “didn’t think it was critical”, and the video analysis (Table 5), which showed it was the second most used technology in the room. This contrast between the perception of the Ambient Display and its actual use highlights the potential for such technologies as persistent representations of critical spatial, informational, and procedural classroom information, that do not require constant attention by the class.

Student and teacher exit interviews further reinforce our perceptions of the effectiveness of these technologies for supporting the classroom orchestration, reducing the orchestrational load, and most importantly freeing up the teacher to work with the students on their ideas.

It was such a shifting paradigm kind of lesson, with the pacing and, the kinetics, and the motion in the room and kids moving around was a lot to follow. [But] I didn’t need to worry about it, it was just taken care of by the various technologies. (Teacher)

With the board it was like ok, this is where we have to go and that’s how much time we have left so we didn’t really need the teacher for that any more... he could just focus more on going around and talking to the groups. (Jen)

It was easy to find out when we first walked in where to go, and the timer [on the Ambient Display] was really clear, compared to teachers or instructors screaming time to move on, because it was visual, even with the flash we can pace ourselves, and it was easy to grab our attention. (Rebecca)

3. Agent architecture’s support of the orchestrational load.
During the in-class pre-activity, the S3 agents provided critical orchestrational support for the teacher. An examination of the server logs show that *Consensus Agent* was able to effectively ensure that each group reached consensus on both the principle tags and equations attached to each of their assigned problems. The *Bucket Agent* was also instrumental in supporting the teacher, through its ability to orchestrate the real-time distribution of problems to individual groups. As soon as a group finished a problem, the *Bucket Agent* dipped into the “bucket” of problems and sent the group a new one, until the bucket was empty. This allowed a large collection of resources to be distributed to groups as they worked in parallel, such that all the resources were attended to in a single 60-minute class. In this way, the *Bucket Agent* was able to accommodate variations in resource difficulty and group skill levels (i.e., some resources were more challenging and some groups were quicker), which resulted in every group finishing within 3 minutes of each other (Figure 32).

![Figure 32: Shaded bars show how many problems the Bucket Agent sent to each group, and time spent on each. For example group 3 took a long time on its problems, so they only received 2.](image)

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In the smart classroom, the *S3 Sorting* Agents successfully sorted students based on the pre-defined criteria described in Section 5.4.2 (Table 9). Both teachers and students remarked on the efficacy of these agents to manage the organization of students around the room based on emergent class patterns and pre-defined pedagogical criteria. The teacher noted that the ability of the agents to orchestrate this facet of the class was particularly useful in supporting his classroom orchestration.

*Each [sort] was a different ensemble, based on all sorts of good physics pedagogy based on where they should be. During transitions when you’re a teacher getting kids up, moving them to different seats – you waste so much class time doing that. Even a common group, cooperative learning scenario, like a games theory thing, where kids are really learning from each other, just getting the kids to move around the classroom adequately for that, I find cumbersome – I just kind of dread moving the kids around the class and organizing that, rather than doing the activities themselves, and so I just loved the logistical assistance that [the S3 agents] offered. (Teacher)*

<table>
<thead>
<tr>
<th>Students</th>
<th>Board A</th>
<th>Board B</th>
<th>Board C</th>
<th>Board D</th>
<th>First sort: Sent to board</th>
<th>Second sort: Sent to board</th>
<th>Sorted to New Board?</th>
<th>Sorted With New Team Members?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alice</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>A</td>
<td>B</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Pearl</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>A</td>
<td>C</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Jason</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>B</td>
<td>C</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Rob</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>B</td>
<td>D</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Desi</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>C</td>
<td>D</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Raffi</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>C</td>
<td>A</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Becky</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>D</td>
<td>A</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Sun</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>D</td>
<td>B</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>
Student Tagging frequencies and Sorting Agent assigned boards for Step Two and Step Three. The agents used a cascading approach to assign one student to Board A based on their frequency of principles, then one to Boards B, C, and D in order, before repeating this process until all student were sorted. For instance Jason was assigned to board B and not A, C, or D because the agent had already placed Alice at Board A, and Jason had the most tags when the agent went looking for a Board B student (i.e., for the second assignment by the agent’s algorithm).

In both the pre-activity and in the smart classroom activity, the Consensus Agents were successful in ensuring that consensus was reached on all of the objects under negotiation by the different groups. During the Assumption and Variable Assignment phase in Step 3 of the smart classroom activity, the Consensus Agents worked with the Student Progress Agents to inform the teacher (on his orchestration tablet) when he needed to approve a group’s work (in order to let them progress in the activity). Over the four smart classroom runs (i.e., out of 16 total opportunities) when the teacher was notified to review a group’s work, in seven cases he had the students revise and resubmit their work, which he reviewed again (Table 10).

<table>
<thead>
<tr>
<th></th>
<th>Zone A</th>
<th>Zone B</th>
<th>Zone C</th>
<th>Zone D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1 Review Alerts</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Day 2 Review Alerts</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Day 3 Review Alerts</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Day 4 Review Alerts</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
Ultimately, by sending the teacher the notification on his tablet, rather than requiring him to constantly keep tabs on the state of every group in the room, we were able to free the teacher to move through the room where he was needed when he was needed.

4. Supporting the teacher as a wandering facilitator.

Drawing from earlier designs, it came as no surprise that the teacher found the large collaborative displays useful in helping orient him to class activities and to engage the students in discussion around their ideas (similar to the “wandering facilitator” of Hmelo-Silver described above). The displays were also the most frequently used tool used the classroom to engage students around their ideas (See table 8 above). The teacher noted that the displays were “large and easily accessible” and that they allowed him to “[walk] over and point to something on [a group’s] screen” to ask them about their decisions or thinking concerning particular aspects of their idea construction. Additionally, placing the groups around the periphery of the room allowed him to “[freely] wander in the middle and not trip over people, moving from place-to-place” where he felt he was needed.

Video analysis of the teacher’s movements during the smart classroom activity support the teacher’s own perceptions of the class. Figure 33 shows the teachers movement within the smart classroom during one enactment of the culminating activity. The teacher made 127 moves during the 60-minute activity, spread fairly evenly across the four zones in the room (Table 11). Many of these moves involved the teacher simply walking up to a group and observing their work, making a brief comment or asking a short question and moving on; however, as the activity progressed and the students’ got deeper into their problem solving the teacher tended to spend
more time with each group (as shown by the flatter “spikes” in Figure 33). This indicates that the teacher was able vary his “wandering” in the room in response to student needs.

I remember he was walking around the room and he was looking at our work on the boards, and gave us some suggestions on our tablets, kinda saying like, oh maybe you could change it or approach it this way, so yeah he gave a lot of feedback while we were doing this activity.

(Christine)

Table 11

<table>
<thead>
<tr>
<th>Zone</th>
<th>Zone A</th>
<th>Zone B</th>
<th>Zone C</th>
<th>Zone D</th>
<th>Middle Table</th>
<th>Neutral Space</th>
<th>Total</th>
</tr>
</thead>
</table>

*Figure 33: Tracking teacher movement in the smart classroom over the 60 minute activity (Note: “Neutral Space” was assigned to locations in the room outside of the 5 main “zones”)*

Total visits by the teacher to zones in the room during one instance of the smart classroom activity. The table shows that the teacher was able to move frequently and evenly across the different “zones” in the room, either simply to check in on students or to engage them in discussion around their thinking or problem solving.
An interesting phenomenon observed during the activity involved the teacher regularly moving to a table (a multi-touch table not used during the activity) positioned in the middle of the smart classroom, and using it as an “orchestration hub” to orient himself what was happening in the class. Most of his time at this “zone” was spent orchestrating class activities, such as looking at his orchestration tablet, checking the Ambient Display, making announcements to the class (e.g., informing them that time was running out or telling them to move to a new station), and looking at the various groups’ displays deciding where he was needed. The results of these observations point to the efficacy of the S3 technology environment, coupled with the physical design of the room itself, to support the teacher as a wandering facilitator during real-time class activities.

5.6 Summary

This study emphasized the role of a pedagogical model in the design and development of a technological infrastructure for Distributed Technology Enhanced Learning (DTEL). Technological environments will best support a specific pedagogical approach if they include explicit supports for the epistemic elements are that are intrinsic to that approach. As such, the design of PLACE, in terms of it adherence to the principles of KCI (the pedagogical model), served as a reference of S3 (the technological model). Through the successful implementation of PLACE within an authentic classroom setting, we were able to successfully reify S3 itself. In doing so, we were also able to come to some deeper understandings about how the various technologies, activity structures, and orchestration scaffolds described above could support the
enactment of a DTEL curriculum. The design of S3 as a technology environment can thus be seen more generally as framework to provide support for the broader orchestration of DTEL inquiry curricula.

The KCI model guided our analysis above, in order to reveal how S3 was developed according to those principles, resulting in a PLACE environment that was able to successfully embed the important KCI principles. While the analysis of this chapter was focused on KCI principles, the design itself was situated within the broader program of design-based research, including the preliminary studies detailed in Chapter 3. Clearly, any of the design principles that emerged from those previous studies should be applicable to S3-based DTEL environments, although we did not make any explicit effort to apply those principles in the PLACE design. The next chapter discusses PLACE (and S3 by extension), as a DTEL environment. To do so, it addresses each of the research questions in terms of the design principles from Chapter 3, in order to understand the technological, pedagogical and orchestrational dimensions. This discussion will serve to further validate S3 as a DTEL environment, and also extend the design principles from Chapter 3 to provide a more comprehensive descriptive framework.
Chapter 6: Discussion

This thesis reported on the design and development of S3, a DTEL framework to support knowledge communities across multiple contexts as they engage in inquiry-based science curricula. The project was a large effort, involving half a dozen technologists at various points throughout the design process, the co-design teacher, the research supervisor and myself, and built upon several earlier design iterations. The outcome of this process was a 12-week curriculum unit that engaged students across multiple contexts (at home, in their regular classroom, in their neighbourhoods, and in a smart classroom), with a focus on student-generated content and a high level of cooperative learning and knowledge construction. A significant component of the research was the design and development of the culminating activity, in which the S3 technology framework supported students in a smart classroom setting as they actively leveraged the community’s knowledge base to solve a set of Hollywood physics problems.

We understood from the outset that a single monolithic technology environment would be unable to support collective inquiry across all possible domains and scripts. As such, the development of S3 was not an attempt to build an out-of-box learning environment, but rather its aim was to give us the building blocks – particularly in regards to data structures, agents, and other dynamically bound “elements” – that would allow us to raise the distinction between the S3 framework and a specific DTEL Environment. We approached the development of S3 knowing a priori that we would like to support a range of DTEL applications and approaches, beyond those of PLACE (i.e., by ourselves and other investigators in the learning sciences). Thus, we deliberately sought technical elements and approaches that would be flexible and extensible, as an open source framework.
This process allowed us to fully design, implement, and evaluate the foundations of the S3 framework for supporting a DTEL curriculum. PLACE was developed using a pedagogical model (KCI) and supported students in learning across contexts and locations, using a variety of personal and collaborative activities, devices, and script configurations. As described in Chapter 5, the resulting curricular design was PLACE - a reference implementation of a DTEL environment within the domain of Physics. Although students’ learning of the required physics content was important to the success of the design (as discussed in section 5.4.3), the focus of this thesis was the implementation of the environment itself – and in turn understanding of how S3 could support other DTEL designs across a wider spectrum of learning domains. Thus, PLACE serves as a reference for S3, and will guide our design of future DTEL curricula.

This chapter opens with a discussion of PLACE in terms of the two research questions, examined through the lens of the design principles for DTEL environments established from the initial studies in Chapter 3. I evaluate PLACE in terms of its adherence to these principles and introduce several new principles for DTEL that came out of the PLACE study. In particular, I expand on the role that (1) locational dependencies and (2) tangible and embodied interactions can play in the development of these spaces and their accompanying inquiry curricula. The chapter concludes by synthesizing the findings of this research into a qualitative framework for research and development of DTEL environments.

6.1 Addressing the Research Questions

This section addresses the research questions in terms of the design principles established during the initial design studies (Chapter 3) and discusses their broader implications for learning sciences research. I also articulate several new principles, which emerged as a result of the
expanded curricular time and wider context of the PLACE research. Taken together, these principles can be seen as important outcomes of this project, and serve as a basis for the discussion.

6.1.1 Research Question 1 (pedagogical): How can a Technology Enhanced Learning Environment support the pedagogical requirements of distributed, collective inquiry?

Following Scardamalia and Bereiter (2006), we understood from the outset in order to support the pedagogical requirements of distributed and collective inquiry we would need to develop technologies that are imbued with the central epistemic commitments of the research (i.e., rather than simply fitting our pedagogy to the affordances of off-the-shelf solutions). Building on the earlier design studies presented in Chapter 3, an important outcome of this research was the first comprehensive design, implementation, and evaluation of such a technology framework (SAIL Smart Space – S3), including a set of recommendations on how these technologies could be used to support future DTEL curricula.

A central challenge in the design and development of S3 was that there were few, if any, other examples of DTEL environment research that we could draw from to inform our designs. While many research programs, including Ambient Wood (Price & Rogers, 2004), Embedded Phenomena (Moher, 2006), Savannah (Benford et al., 2004), and even Knowledge Forum (Scardamalia & Bereiter, 1992) have elements of DTEL, none have advanced technology environments that are specifically purposed to capture a community’s emergent knowledge and make it available for purposes of inquiry, distributed within and across learning contexts.
Because there were no other comparators, this work served as a foundational effort that will be referenced by ourselves and others in future research.

To discuss how PLACE helps to address the research question, I evaluate the Pedagogical and Technological Design Principles from Chapter 3, in terms of what PLACE did right and where it fell short, with the goal of improving future DTEL designs.

**Pedagogical Design Principle: Student inquiry should be informed by emergent, aggregate representations of the knowledge community’s progress**

We understood from the outset, that one of the major challenges in supporting students as a knowledge community was the need for them to be able to see their own work and the work of others as part of the larger community, and use this work to support their own inquiry needs (Hewitt & Scardamalia, 1998; Gilbert & Driscoll, 2002, Hoadley & Kinler, 2005). Over the course of sustained inquiry, as the knowledge base grows, connecting students with relevant and meaningful material from the knowledge base becomes increasingly difficult (Leinonen et al, 2002; Rico & Shulman, 2004). In designing S3, within the context of PLACE, we developed several approaches that allowed students, to both see themselves as part of the community, and actively take part in it.

In PLACE.web, students were able to see both the activity around their individual contributions to the knowledge base through the aggregated newsfeeds, and the growth of the collective knowledge base through the Associative Web. Of the seventeen students who completed the post-test question on the Associative Web, sixteen found it useful for seeing and filtering the overall knowledge base. The one student who did not find the web useful did note that “if there
were more examples (and information to sort through) it could really help with organizing concepts,” pointing to at least the understanding of the Web’s utility within a growing knowledge base. Although this points to the success of the Associative Web in making information available to support student inquiry, it’s unclear at present how far this would scale. Features such as the date filtering were available with the Associative Web, in an attempt to address this, but they did not seem to be heavily used by the students (no students reported using the date filtering during the post-test, but it was not expressly asked about either).

As outlined in Section 5.3.3, the students were able to successfully leverage the interactive collaborative displays to build on the prior contributions of their peers in order to solve the Hollywood video problems. These aggregates point to the interesting potential of such displays to persist over longer scales of time that those presented in this study. As the cycles of inquiry get extended, such aggregates have the potential to become instrumental in orienting students to the growth of the community’s ideas, to highlight avenues for discussion or debate, and as a starting point for the day’s activities.

*Pedagogical Design Principle: Curricular scripts should be structured to include individual activities that feed into larger collective goals.*

Throughout the PLACE curricula, individual student contributions to the knowledge base were used as a resource for supporting the larger community goals. The individually contributed examples of everyday physics were used as a basis for spurring discussion among students to help them collectively see the role physics plays in their daily lives - a central epistemic goal of the co-design teacher.
In Section 5.3.2, I discussed how small groups used the community-contributed artifacts in the development of class “Challenge Problems”. These problems were then reused once again in the culminating activity, both during the individual homework activity and as evidence for supporting students in solving the Hollywood video problems in the smart classroom.

This movement of students and materials between individual, collective, and collaborative tasks was a central facet of the PLACE design, and one in which we felt S3 would be instrumental in supporting. This was particularly true during the three stages of the culminating activity, as students moved between the individual task of tagging problems at home; to collaboratively negotiating the final tags and equations for the homework problems in small groups while in class; and finally in the smart classroom, where students alternated between collective tasks (e.g., submitting tags during Step 1, or problems during Step 2) and collaborative tasks (e.g., building consensus on the collectively submitted artifacts throughout the activity, and their construction of their final answers).

Throughout this process, S3 maintained an awareness of where students were in the room, where in the script each student was, and whom they were grouped with. The DTEL environment was able to use the underlying agent infrastructure, data mining, and real-time messaging to coordinate the both the flow of materials to students on their individual devices, and from the individual student devices to the collaborative displays. The outcome of this coordination was highlighted in section 5.4.3, which mapped out how the individually submitted and collaboratively negotiated materials (on the collaborative interactive displays) played an important role in supporting the student final solutions.
Pedagogical Design Principle: Students should be supported in critical reflection as both a product and a resource for the learning community.

During the initial 12-week PLACE.web portion of the activity, critical reflection was an important element in facilitating students’ development, sharing and negotiation of ideas surrounding the 14 core physics principles. When engaging in discussion and reflection in PLACE.web, students were required to follow a specific script in which they had to vote on the underlying principles, in addition to adding to the evolving discourse on any specific artifact (similar to the TAR script enacted in the preliminary design studies). This script resulted in the development of a robust knowledge base, around which students actively engaged as a community and supported them in their understanding of physics in their everyday lives. As one student noted, “physics is just everywhere around us, that we can use these equations in really everything that happens around us, it’s not as distant as I really thought it was” (Sam).

There was notably less scripted reflection within the culminating activity, although students were tasked with explaining their choices of negotiated homework problems during Step 2 and in their final recorded answers. Although this was partially due to the time constraints of the activity, it resulted in some students mentioning that it decontextualized the contributions of their peers (e.g., why did their peers think “Newton’s First Law” applied to the video?). In the case of PLACE.neo, students were still able to successfully complete the activity with a high degree of accuracy and Knowledge Integration (see Section 5.4.3); however, it does point to the need to include scripts that explicitly require students to critically reflect on the reasons for their contributions (even if it is simply adding an existing artifact in a new context) in order to properly contextualize it for the broader community.
Pedagogical Design Principle: Assigning expertise groups can help distribute knowledge across the community and provide support for further distributed tasks.

Throughout the PLACE curriculum, the assignment of expertise groups played an important role in managing the load placed on students and ensuring that the community’s required pedagogical needs were addressed. For all three units (Kinematics, Forces and Motion, and Work, Energy, and Power) each student was assigned as an expert to a subset of the unit’s principles. Coupled with the end-of-unit review of their peers examples, we found that this ensured that not only were all the principles covered by the class as a community (with students engaging with on average 13.6 of the 14 principles - Section 5.2.3 above), but that it also provided students with new perspectives outside of their own expertise:

* I did the second law, and so I started recognizing how things related to Newton’s Second Law related to my life around me, but less about the 1st law or the 3rd law because I didn’t really think about where can I find these examples. But because I had the opportunity to talk to students who had analyzed what they can see around them, and examples of those laws that they learned in class, talking to them really helped me... It was interesting because it was something that I wouldn’t have really thought of, even working with people who worked on the same project as me, they had examples that I would have never thought of, so that was interesting [and] it was really helpful. (Rebecca)

The distribution of expertise across the community also played an important role in the culminating activity. During the at-home homework phase the problems that students answered were divided up based on their individual expertise – we didn’t want every student to have to review all 30 questions, but we wanted to ensure that students with expertise in each principle saw the problems at least once. This allowed us to reduce the load placed on each student...
individually while ensuring that the artifacts were attended to by the community’s collective expertise.

During the Principle Tagging activity in the smart classroom (Step 1), by giving students their expert principles on their tablet, we allowed students to focus their tagging of the videos to those principles they were most familiar with, rather than requiring them to think about all fourteen.

The sorting of students (i.e, by the Sorting Agent) based on their tagging frequency (between Steps 1 and 2) highlights another interesting avenue for the emergence of expertise within a community. By sorting students based on their past actions, we open up the possibility for shifting and dynamic expertise in the community, and for connecting students (to each other or materials in the knowledge base) based on these conditions. This is an ideal match to the notions of an evolving and emergent knowledge community focused on inquiry, and although only preliminary, shows some exciting promise for agent supported distributed intelligence and community expertise.

Hence, the four pedagogical principles from Chapter 3 provide a good lens for understanding PLACE as a DTEL, and offer a secondary source of analysis indicating a good fit to our definition. However, because PLACE expanded the learning design to include longer duration and multiple contexts, several new principles are also suggested, which can be added to the set from Chapter 3. Here I introduce one new pedagogical principle, and sections below will follow suit.
Pedagogical Design Principle (new): In order to bridge different learning contexts, visualizations of the community knowledge must present the aggregated information in ways that are contextually relevant to the present location and activity.

During the enactment of PLACE, students were often required to engage with the community knowledge base across multiple learning contexts (at-home, in their neighbourhoods, in class, and in the smart classroom). In order to facilitate productive learning and community engagement, we needed to consider the specifics tasks required by students in each context, their individual and collective roles, and the informational requirements to successfully complete each task. In PLACE we needed to consider the transition from the individually collected examples to collaborative online activities. We wanted student-contributed inquiry artifacts to be the focus of the activities (rather than materials found in textbooks or other professionally curated materials). Our main challenge was finding ways for the students to effectively search a large repository of student artifacts to find materials that fit their specific needs. In response, we built the Associative Web, which allowed students to mine artifacts based on their assigned tags, and present them in a ways that were useful to their given context.

At home, we wanted students to see how in-class activities affected their own contributions to the knowledge base. This was the impetus for the aggregated newsfeeds, which leveraged system generated metadata about individual students (e.g., which artifacts they had worked on), providing them with contextualized updates and a macro view of the whole class’ activities. These different aggregated and filterable views served as a bridge for students to orient themselves within the larger knowledge community.
During the culminating activity we needed to visualize the aggregates of the community’s contributions specifically to fit each context and task. At home, the students only saw their own answers to the tag and principle assignment of the homework problems. In class, we wanted the groups to build off the collective work of the class and their peers in real-time, which required an aggregate visualization of the individual work the students did individually at home. In the smart classroom, the individual elements of the problems (their assigned tags and equations, and the problems themselves) were separated and shown to students in order to support their specific activity (e.g., when they were tasked with picking equations during Step 3). By using the JSON/MongoDB data structures, S3 was able to pull and aggregate from the database only those elements of an artifact that were relevant to a student’s current task, helping to reduce their information processing load.

By representing the knowledge in ways that are relevant to the task at hand, these visualizations become powerful boundary objects in support of the community’s distributed cognition (Arias & Fishcer, 2000). Within inquiry curricula, learners may bring different perspectives or ideas, based on their individual areas of expertise (in for example Jigsaws) or prior knowledge; as such, boundary objects can play an important role both in creating shared understanding and a contextualizing the information. Within DTEL, and in inquiry curricula in general, this becomes increasingly important, as there is a persistent challenge in creating possibilities for participation and collaboration both within and across a diversity of learning contexts (Akkerman & Bakker, 2011). As learning designs become increasingly distributed, such boundary objects should offer the potential to support collaboration and knowledge building simultaneously across multiple
physical and social planes (e.g., students at a marsh engaging and sharing information in real-time with students in a classroom).

*Technology Design Principle: Small group interactions can benefit from the use of large, shared displays that support collaboration and idea refinement.*

Section 5.3.3 discusses how PLACE satisfied this principle through the use of the collaborative interactive displays at each zone in the room, by supporting group interactions, discussion and idea negotiation. It important to note that in PLACE, the interactivity with the displays was enabled through the uses of wireless trackpads, which the students could pass around in order to manipulate objects on the screen. The use of trackpads allowed students to stand several feet back from the displays while they collaborated. Although effective, it does raise the question of how students might have behaved if they were required to stand right in front of the screen (to touch the screen directly). What forms of collaboration would take place if the students were able to simultaneously manipulate the objects on the display, and how would students occluding the display (blocking other students from seeing what is on the displays when standing in front of it) effect collaboration?

*Technology Design Principle: Handheld computers offer increased mobility within the DTEL environment.*

Handheld computers (smartphones and tablets) played two important roles in the enactment of PLACE. First, during the 12-week PLACE.web curriculum, students were able to use their smartphones to capture examples of physics in a wide range of contexts and locations, including at a school track meet, at a friend’s pool party, on a subway, in their basement, and in the halls of
their school. In this way, we were able to extend the classroom beyond its traditional walls and distribute the community’s understanding about physics across these spaces as well. Although there were many interesting student-contributed examples, almost as many were simply grabbed from the web, either as static images or as YouTube videos (Table 4 in 5.2.3 shows that 55 original videos were submitted by students compared to 48 embedded YouTube videos). Part of the reason for the high number of YouTube videos may be because it was simply easier for students to search for examples that fit the their criteria, than for them to capture examples “in the moment”. Another reason may be that at the time of the research, mobile web browsers were not as sophisticated as the are now, and uploading rich media to PLACE.web was often very difficult, (if at all possible) on most Apple iOS devices (i.e. iPhones and iPads).

Despite these technological shortcomings, overall we deemed S3 and PLACE.web a success in this regard. Perhaps the most telling illustration of this was the episode in which co-design teacher reported that he was stopped in the hall by a group of students who were debating an example that was displayed on one the of the students’ phone. Not only had the contribution of artifacts to the knowledge base been extended beyond the classroom walls, so to had the discourse and enthusiasm for inquiry.

During the culminating activity, the introduction of handheld tablets added a layer of student mobility that was not present in the earlier design studies. During the 65-minute activity, each student moved to a new zone six times, four of the moves were decided by the students themselves (free-roaming) and two of the moves were directed by S3’s software agents. Several students noted that this ease of movement helped them move between the various inquiry topics,
which in turn helped to spatially index the class’ inquiry, and provided them the opportunity to see what other groups had been working on.

*Just being able to move while you work and not just writing down things so taking the tablets turning things around helped me, give me a spatial sense of what I was learning.* (Sam)

*Moving around is always nice. It was more engaging, not just watching the same video the whole time, also you want to see what other people are watching and what other people are doing.* (Sarah)

Even though in the previous designs students were given laptops (technically a portable technology), their size and weight made unfettered movement much more difficult than with the tablets. From the recorded video of the runs, we found that the tablets allowed students to more easily hold the devices (rather than the laptops), to interact with (such as swiping and touching elements), and to share what was on their screens with their group members.

*Technology Design Principle: Tracking users within a DTEL environment offers unique opportunities for ad hoc groupings and collaborations.*

In the culminating smart classroom activity, the ability of S3 to successfully track users locations in the physical space was fundamental to the successful enactment of the curriculum. In conjunction with the bucket agent, knowing which and how many students were grouped at each board around the room allowed S3 to evenly distribute tasks and materials (e.g., a zone’s filtered set of problems drawn from the database) between them. Unlike in the initial design studies, where students we all given the same content when they were logged into a zone, during this implementation we were able to provide contextually and script relevant, but distinct, materials to each student.
The ability to track students within the DTEL environment also allowed S3 to connect student-generated artifacts to the students’ locations in the room. For instance, during Step 1 (Principle Tagging), S3 was able to send (in real-time) the tags that students individually attached to each video to its interactive collaborative display. This provided a degree of freedom to students in the room, allowing them to go wherever in they wanted, in order to engage with different grouping of peers or different inquiry elements. Although the movement of students within the room, and their engagement with the materials at each zone, was somewhat limited because of the linear progression of the script, and the limited duration of the activity (one sixty-five minute class), it does highlight the potential for S3 to support longer duration and less coerced inquiry scripts. It is conceivable that a different DTEL curriculum could engage students in longer investigations, in which the products of inquiry evolve over several sessions in the DTEL environment. In such cases, the ability to support students as they move throughout the room spontaneously, collaborating with their peers and contributing to a particular facet of the inquiry in a more ad hoc fashion, becomes integral to the success of the curriculum.

*Technology Design Principle: Automatically updating devices based on real-time conditions can support rapid transitions within and between activities (e.g., feedback, delivery of materials, re-grouping of students).*

Building off of our earlier designs, the ability to update devices and displays in real-time was one of the cornerstones of the development of S3. During the in-class portion of the culminating activity, where students needed to reach consensus on the final set of principle tags and equations for each of the homework problems, the real-time messaging in S3 was instrumental in supporting groups as they engaged in debate and negotiation. On their tablets, students could see
which of their group members they agreed with and on which elements. As students changed their choices (e.g., which principles they felt applied) their choice would show up on the tablets of their group members (Figure 34).

During the smart classroom activity, as a group completed a task (e.g., the negotiation of principles in Step 2), the S3 messaging system was able to update the zone’s interactive collaborative display, the ambient display, the teacher’s orchestration tablet, and provide the group with the next task (or in the case that they were finished the step, a notification to wait for further instructions).

As discussed in Chapter 5, when the teacher moved the class to the next step in the activity using his orchestration tablet, S3’s real-time messaging architecture (in conjunction with S3’s intelligent agents) was able to instantly send each student individual instructions about where to go in the room. By connecting all the devices in the room, we were able to better coordinate both the flow of materials between and across students, and the movement of students themselves within the room.

Figure 34: A student tablet during the in-class activity. As students made choices, every group member’s tablet would be updated in real-time. A group couldn’t progress until all members had reached consensus.
Technology Design Principle (new): To facilitate the organization of student materials for use across contexts, data structures should be defined to support flexible query and representation by students, and access by intelligent agents.

Examining S3 through the four technological principles derived in Chapter 3 provides corroborating evidence of S3’s fulfillment of the requirements of DTEL. However, as with the pedagogical principles, the expansion of the curriculum in PLACE, both in duration and across contexts, highlighted the need to consider an additional technological design principle for support DTEL curricula.

During the culminating activity, an important transition concerned the movement of materials and student roles between the at-home stage (i.e., on PLACE.web) and the in-class stage (using the PLACE.neo tablet apps in the classroom). In order for small groups to work on the assignment of principles and equations in class, we needed S3 to aggregate the individual homework responses in ways that fostered collaborative discussion and debate. Because the underlying metadata were semantically well-defined (e.g. using tags such as “problems”, “principles”, “equations”), we were able to easily create views that supported the desired scripted interactions. Metadata also played a significant role in connecting the in-class artifacts to the smart classroom. In the smart classroom, S3 agents could easily leverage the semantic metadata generated by students during the activity around each video (e.g., their negotiated video tags), to query all artifacts that had been tagged similarly during the in-class stage. These metadata allowed information to flow seamlessly across contexts and to be repurposed for the particular scripted goals within each context.
6.1.2 Research Question 2 (orchestrational): How can a DTEL environment address the current challenges to the successful enactment of knowledge community curricula?

By examining the PLACE implementation through the lens of the DTEL design principles, we can develop several important understandings of the role that a framework such as S3 could play in supporting the orchestration of a knowledge community engaged in an inquiry curriculum. A significant challenge in developing such curriculum is being able to articulate the role of the teacher in the DTEL experience. A well-designed DTEL environment can move the teacher away from being simply a “sage on the stage” or an administrator of class activities to an active co-participant in the knowledge community. The ability to off-load many of the administrative and regulative tasks of the class onto the system itself (by leveraging real-time messaging and agent architectures) can free the teacher to focus on engaging with the students and their ideas directly.

As co-participant in the knowledge community, the teacher still plays an important role in providing timely feedback and guidance to students. Frameworks such as S3 can help the teacher in this role, through the development of tools that allow for the intervention to take place, and through the development of alerts and other orchestral supports to inform him or her when intervention is needed.

Below, in order to understand the effectiveness of S3 in supporting the orchestration of a knowledge community curriculum, I revisit the DTEL orchestration design principles outlined in Chapter 3 and discuss S3’s adherence to these principles in terms of the PLACE design.
Orchestrational Design Principle: Avoid actively designing a “heads down” experience for the teacher.

As discussed in Chapter 3, developing interfaces that promote a “heads down” experience pose an orchestrational challenge by preventing the teacher from seeing what is going on around him or her (e.g., instead forcing them to focus on a tablet screen). During the PLACE.neo culminating activity, as shown in Section 5.5.3, the combination of the collaborative interactive displays and the re-designed teacher orchestration tablet, were effective in promoting a more “heads up” experience for the teacher. This allowed him to see the products of the different groups around the room, and to make decisions about where he was needed. One possible concern, observed across the four sessions of the culminating activity, was that the teacher still tended to put the tablet down when he wasn’t using it, making it possible for him to miss orchestral prompts. Part of the reason for this may have simply been the design of the script itself: there were only a few “vital” orchestral prompts that the teacher needed to attend to (i.e., when he needed to approve students variables and assumptions in Step 3). Otherwise the orchestration tablet was mainly used to ensure every group had completed the task (not necessarily actionable, and did not require his constant attention) and to move the class to the next step in the activity. However, this did seem to promote a practice of him not having the tablet with him at all times, which did cause some delays from when a group’s Progress Tracking Agent sent out a request and when the teacher went to talk with them. Video analysis similarly revealed that in some cases the teacher had the tablet in his hand but wasn’t aware a prompt has been sent as the screen was off or he wasn’t looking directly at it.
This suggests that an additional layer of notification may be necessary to alert the teacher about an “orchestratable moment” in the script. These may include auditory (such as a beep) or haptic notifications (such as the tablet buzzing) to draw the teacher’s attention to the tablet if it is in their hands or close proximity. Additionally, some facets of this notification could be transferred to the ambient and interactive displays. Adding visual cues to these displays (such as glowing boarders or other semantically relevant representations) could support both the heads up experience of the teacher, and gives the students themselves a clear indicator that their request has been processed (and the state of other groups around the room).

*Orchestrational Design Principle: Large, dynamic representations of student work can provide ambient cues.*

As noted by Sharples (2013), making the work of students and the progression of class activities available and actionable is a significant orchestrational challenge, and one that we felt from our own earlier studies (Chapter 3), could be addressed through the use of large-format vertical displays. These displays could provide important ambient cues to the teacher about where he was needed based on emergent class patterns, and procedural information to the whole class (such as the timing of tasks), at the periphery of their attention.
The various large-format displays (i.e., each zones’ collaborative interactive display and the two ambient displays – Figure 35) designed for the PLACE DTEL environment were instrumental in helping the teacher make decision on-the-fly. Table 8 (in Section 5.5.3) showed how the two types of large displays helped the teacher in enacting specific orchestrational moves; however, their greater utility may have come from their ability to help the teacher decide where to go in the room at any given moment. When tracking the teacher’s movement around the room (Figure 33 above), the teacher was often observed looking at each zone’s collaborative interactive displays before making his decision where to go. Exit interviews with the teacher support our observed effectiveness of these displays as he noted that “the displays were large and easily accessible” and compared to the orchestration tablet, “the visual clues on the [large] display screens, in retrospect, seemed like a better idea to [him] now” for orienting him to what was going on in the class. As with the earlier design studies he noted that the large displays didn’t prevent him from “just looking around the room” the way that the orchestration tablet did. These

Figure 35: The teacher observing student work on their interactive collaborative display from a distance to determine if the group needs his assistance.
comments from the teacher, in terms of the orchestration tablet versus the large displays, mirror the conclusions drawn from the above orchestrational design principle focused on avoiding a “heads down” experience for the teacher. This further points to the need to think critically about what we place on a “heads down” device like a tablet and on “heads up” displays such as those presented in PLACE.neo.

In terms of the front ambient display, as reported in Chapter 5, the tool was effective as a persistent and unobtrusive indicator of the class’ activities and the timing of tasks. Much of this can be directly attributed to the ability of S3 framework’s messaging system to represent events in the room as they happened in real-time. The teacher noted that the task timer was particularly useful in helping him stay on track, focused, and ensured that everything was completed during the allotted classroom time.

The combination of these two types of large displays – those that show the growing aggregate of student-generated work, and those that provide alternative lenses into the state of the class (such as timing, positioning, or progress) – offer a promising avenue for providing teachers and students alike important information at the periphery of their awareness, and to help in real-time orchestrational decision making.

*Orchestration Design Principle: Notification and feedback about activity states should be actionable and timely.*

Building off the insights gained from the initial design studies, support for effective feedback and prompts was a major consideration in the PLACE.neo implementation. On the teacher’s orchestration tablet, prompts (managed by the *Progress Tracking Agents*) informed him when
each group was finished an activity and when a group needed his approval of their assumptions and variables. Unlike in the earlier studies, where the notifications weren’t actionable, in PLACE.neo the prompts were designed to give the teacher important cues on the state of the class that helped him to support him in making real-time orchestral decisions.

Throughout the runs the teacher was observed referring to his tablet to make sure every group’s status indicated they were finished before progressing the class to the next step in the activity (see Table 8 in section 5.5.3). It was interesting to note that throughout the runs the teacher adopted a practice of confirming that the status on the students’ tablets matched what was shown on his own, by asking the class if everyone was “cat-ish” (referring to the waiting screen which showed a picture of a cat – see figure 36). It is unclear however if the teacher did this because he didn’t trust his own display or he simply wanted to draw the students’ attention before progressing them to the next step.

The orchestration tablet notifications that instructed the teacher to review the assumptions and variables of each group were a significant departure from those in the initial designs, as they gave the teacher true actionable information that allowed him to directly engage in students’ knowledge construction and inquiry. Figure 29 in section 5.4.3, showed how these prompts were not only actionable, but they also produced increased learning outcomes for the students.
Although there is some question about whether displaying this information on the teacher’s orchestration tablet (or on one or more of the large-format displays in the room) is the ideal configuration, there is a clear capability for S3 to track this progression of tasks, provide the necessary notifications, and their effect on supporting the real-time orchestration of activities.

_Orchestration Design Principle: Intelligent software agents can help coordinate the flow of activities and materials based on emergent patterns within the environment._

The extensive analysis in Section 5.5.3 showed the central role that agents played in supporting the orchestration of class activities – from the distribution of timely materials, to the monitoring of student progress, and the assignment of groups, the S3 intelligent agent infrastructure was able to leverage emergent class data to support student inquiry needs.

Within PLACE, the effectiveness of the S3 intelligent agents’ to process information that was intentionally ill-defined at the outset (i.e., information that could not be known _a priori_ rather could only be known through the curriculum’s enactment), provides insight into the role agents can play in orchestrating DTEL designs. This mirrors the view of Roschelle, Dimitriadis & Hoppe (2013), who suggest there is considerable promise in being able to adapt curricula, recommend materials, and support collaboration through the processing of emergent learning traces and metadata connected to the artifacts and participants in a knowledge community.

This implementation of the S3 agent architecture is a first step at realizing the role that agents can play within an emergent inquiry curriculum. Although the bulk of these agents were concerned with facilitating orchestration across a single classroom setting (such as in the in-class and smart classroom activities), we understand the potential for them to support broader cycles...
of inquiry, in which student generated products and collaborations are spread over longer scales of time. In such cases, knowing which information in the knowledge base is relevant to a specific student or group’s inquiry needs can become less clear, and the role agents can play in connecting them with this information, and thus as an integral part of the community’s distributed intelligence significantly increases.

**Orchestrational Design Principle (new):** *The inquiry script should include timely opportunities where students are able to revisit, review, or refine past community work in order to address misconceptions, add new information, or re-engage with earlier ideas.*

In comparison to our initial design studies, the culminating PLACE activity placed a significantly higher orchestration load on the teacher, as it required him to hold more of the design in his head, and to (potentially) connect student work and past actions from one context to another. Evaluating S3 in terms of the orchestrational design principles above, we highlight its ability to support this increased complexity, while still supporting the central goals of the DTEL approach. This increased complexity, also resulted in a wider range of student generated artifacts and scripted forms of collaboration, which in turn, brought to light a new orchestrational requirement within the framing of DTEL design principles. Below I describe this new principle in terms of the PLACE enactment.

One particularly interesting aspect of students’ interactions within PLACE was their retaining a larger than expected set of negotiated equations (as a sort of “tool belt”). Within the activity, students were aware that once they made a decision to *drop* an equation from their set, it would no longer be available for them to use them later on. This meant they had to keep potentially
extraneous information until they were sure it was not needed. During his exit interview, the teacher noted that at some points in the activity it was possible that:

[the students] made a decision about whether they needed an equation and then later realized that they had sort of gone down the wrong path... I think it would be nice, if we do this again, that we add a feature where they could go back... almost an extra layer of little more open ended [progression].

Within an inquiry investigation, especially longer inquiry investigations such as those described in the paragraph above, new insights and information can often emerge that were not previously known, requiring students to revisit prior information and reconsider or refine their previous thinking.

It is important to note, that in the design of a DTEL curriculum not all activities need the ability to be revisited. When deciding on whether or not to make an artifact or activity revisitable, it is important to consider the impact of not being able to revisit it will have on the community’s persistent knowledge, and students’ ability to complete current and future tasks. In PLACE, students were able to complete the “Equation Negotiation” task, however they needed to work around the restrictions placed on them in order to do so. Conversely, during the “Assumption and Variable Negotiation” task, the teacher was able to have the students refine their final set before having them move on. The result was a higher percentage use of assumptions and variables in their final solutions than of their negotiated equations (76.8% of the assumptions and variables versus 54.6% of the assigned equations, as shown in Section 5.4.3).

There remains a need to better understand the levels of strict adherence to a specified script, described by Dillenbourg (2002) as “coercion” that should be required at any point within the script. Depending on the activity and the desired pedagogical outcomes, students may need to be
able to revisit previous tasks, or edit or modify knowledge artifacts depending on the emergence of new understandings. This produces some challenging tensions for pedagogical designers, as they have to balance the need to progress through the scripted activities at a reasonable rate (and to produce specific knowledge artifacts), without compromising the opportunities for supporting unexpected learning moments.
Table 12

*Orchestrational, Pedagogical & Technical design principles for DTEL environments and examples of their use in the S3/PLACE implementation.*
<table>
<thead>
<tr>
<th>Orchestral Design Principle</th>
<th>Description</th>
<th>S3/PLACE Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student inquiry should be informed by emergent, aggregate representations of the knowledge community’s progress</td>
<td>Reduce the amount of time the teacher needs to look down to increase his or her ability to scan the room and interact with students.</td>
<td>Orchestration tablet did not require the teacher’s constant attention. Large format collaborative displays allowed the teacher to keep his “head up” while making orchestration decisions.</td>
</tr>
<tr>
<td>Large, dynamic representations of student work can provide ambient cues</td>
<td>Supports the teacher in making real-time orchestration decisions by providing him at-a-glance insight into the work of the groups distributed around the room. Helps make student work and class dynamics visible and understandable on-the-fly.</td>
<td>Ambient displays leveraging the S3 messaging protocol gave the class important cues including students’ locations and timing of tasks.</td>
</tr>
<tr>
<td>Notification and feedback about activity states should be actionable and timely.</td>
<td>Need to understand how feedback and prompts fit into the flow of activities. Information or prompts that are not actionable or disrupt the flow of activities should be reconsidered in terms of when they occur (or if they should occur at all).</td>
<td>S3 messaging system notified the teacher when all groups were done an activity. Teacher was notified on his orchestration tablet when he was required to review student work.</td>
</tr>
<tr>
<td>Intelligent software agents can help coordinate the flow of activities and materials based on emergent class patterns</td>
<td>Intelligent agents can track and respond to emergent class patterns in order to make real-time scripting decisions.</td>
<td>S3 intelligent agents were able to process information that was intentionally ill-defined at the outset to deliver materials, send notifications, and form groups on-the-fly.</td>
</tr>
<tr>
<td>Some scripted activities require students to be able to revisit, review, or refine past community work in order to correct prior misconceptions, add new information, or re-engage with the ideas</td>
<td>Within inquiry curricula new insights and information can emerge that were not previously known, requiring students to revisit prior information and reconsider or refine their previous thinking.</td>
<td>During the culminating activity the teacher could send students back to re-do their assumptions and variables. Teacher did note more a potential need for flexibility for greater flexibility in future designs.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pedagogical Design Principle</th>
<th>Description</th>
<th>S3/PLACE Implementation</th>
</tr>
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</table>
Student inquiry should be informed by emergent, aggregate representations of the knowledge community’s progress. Aggregate representations can support student problem solving, developing higher quality domain specific insights and the formation of a cohesive knowledge community. In PLACE.web aggregated newsfeeds showed the emergent activity of the community, which could be further filtered using the Associative Web. In PLACE.neo students used the interactive collaborative displays to build on the prior contributions of their peers to solve the Hollywood video problems.

<table>
<thead>
<tr>
<th>Curricular scripts can be structured to include individual activities that feed into larger collective goals</th>
<th>The products of individual student work can be leveraged for larger group and class-wide goals.</th>
<th>Individual student-contributed artifacts in PLACE.web became evidence to support problem solving in the culminating activity. S3 coordinated the movement of individual artifacts to collective and collaborative spaces (interactive displays) during the culminating activity.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support students in engaging in critical reflection as a product and a resource for the learning community</td>
<td>Reflection plays a central role in externalizing conceptions, and reexamining and revisiting one’s own understandings and views. Critical reflection is important in facilitating students developing, sharing and negotiation ideas as a community.</td>
<td>In PLACE.web students provided reflections when contributing or debating on examples of real-world physics. In PLACE.neo students were required to provide a reflection on why they chose their scaffolding examples, and during their final recorded video answers.</td>
</tr>
<tr>
<td>Assigning expertise groups can help distribute knowledge across the community and provide support for further distributed tasks</td>
<td>By assigning expertise groups, students can focus on one area of a larger inquiry investigation or task. Students can then bring their individual understandings to larger distributed group activities (e.g., Jigsaw activities)</td>
<td>In PLACE, students were given a subset of the class’ principles to become experts on, giving them a unique perspective when engaging with their peers. S3 agents identified students for inclusion in “expert groups” during the culminating smart classroom activity.</td>
</tr>
<tr>
<td>In order to bridge different learning contexts, visualizations of the community knowledge must present the aggregated information in ways that are relevant to the present context and activity</td>
<td>Visualizations are powerful boundary objects to support a community’s distributed cognition, by representing the knowledge in ways that are relevant to the task at hand, creating shared understanding and a contextualizing the information. During the culminating activity, S3 customized the visualization of students homework problems at-home, in-class, and in the smart classroom to support specifically designed pedagogical interactions.</td>
<td></td>
</tr>
<tr>
<td>Handheld computers offer increased mobility within the DTEL environment</td>
<td>Smartphones and tablets can allow students and teacher the ability to easily move through the DTEL and to provide information and scaffolds based on their location.</td>
<td>PLACE.web allowed students to capture examples of physics in their everyday lives on the smartphone extending the learning beyond the classroom walls. In the smart classroom students and teachers we free to move around the room with their tablets giving them detailed instructions and location specific materials.</td>
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<tr>
<td>Small group interactions can benefit from the use of large, shared displays that support collaboration and idea refinement</td>
<td>Large shared displays can be uses as a common referent by group members, by making individual ideas visible to the group, supporting simultaneous manipulation of shared artifacts and visual supporting for engaging in debate.</td>
<td>The interactive collaborative display in the smart classroom activity helped students negotiate ideas, and as a reference for constructing their final answers.</td>
</tr>
<tr>
<td>Tracking users within a DTEL environment offers unique opportunities for ad hoc groupings and collaborations</td>
<td>Tracking students’ location within a DTEL environment can connect their generated artifacts to locations in the room, and students with other who co-occupy a space or who are distributed across multiple connected spaces.</td>
<td>The S3 Pub/Sub messaging architecture was able to know where each student was in the room (based on their logging in or assignment by an agent), and provide them location specific materials and display their contributions on the “zone’s” collaborative display.</td>
</tr>
<tr>
<td>Automatically updating devices based on real-time conditions can support rapid transitions within and between activities (e.g., feedback, delivery of materials, re-grouping of students).</td>
<td>Connecting the devices in the room can allow for the coordination and flow of instructions and materials between and across students, and the movement of students themselves within the room.</td>
<td>During the in-class homework problem review, S3 automatically updated groups’ tablets to show them the choices made by their peers to support discussion. In the smart classroom, when a group completed an activity the S3 messaging instantly updated the ambient display, and the students’ and teacher’s tablets.</td>
</tr>
<tr>
<td>To facilitate the organization of student materials for use across contexts, data structures should be defined to support flexible query and representation by students, and access by intelligent agents</td>
<td>Data structures and metadata can allow information to flow seamlessly across contexts to be repurposed for the scripted goals within each.</td>
<td>In the smart classroom, S3 agents leveraged semantic metadata generated by students to provide materials that had been similarly tagged in class.</td>
</tr>
</tbody>
</table>

### 6.2 Tangible and Embodied Interactions
While somewhat outside of the scope of this thesis, an aspect of interest to this study was the role that tangible and embodied interactions play in DTEL settings (especially in environments such as the smart classroom during the culminating activity). In such learning environments, the physicality of the space itself and the relationship that students have with each other and the tasks at hand are important factors in understanding and supporting learning. Winn (2003) asserts that cognition involves our entire bodies and not just our brains. As such, cognition is thus embodied in the physical activities of learners, and the activities are embedded in the learning environment in which the cognition takes place, and therefore learning is ultimately the result of the adaptation of the learner to the environment and the environment to the learner.

In the PLACE.neo smart classroom activity, student interactions were physically indexed to the room itself, by the technologies embedded in the room (i.e., in particular at each zone and at the front of the class) as well as via intelligent agents that made locational assignments. By distributing student activities across the physical space of the learning environment and in the technologies that mediated these spaces, we were able to create and mediate meaning between individual students, their co-located peers, and the larger knowledge community.

Vaerla et al. (1991) assert that the way we organize ideas directly reflects how we act in the world, and that cognition consists of the constant, reciprocal interaction between the mind and the environment. This suggests that having students interact with their ideas in a physical and tangible way may have some direct influence on the nature and quality of learning. In PLACE, the tangible nature of the interactive collaborative displays (i.e., students’ direct, physical manipulation of their ideas on the screen) helped foster student interactions with their ideas and encouraged high levels of engagement.
I thought it was funny because like sometimes we didn’t agree on which concept and stuff so people would like move one in and then move one out again [laughs] so I think that the wall let people change their minds are really put their thoughts into a material way, but it was easily changeable versus using an actual paper, like if your wrote down in marker that you thought this idea was relevant then it would be a lot harder to get rid of it and change your mind if you decided it wasn’t relevant. (Pearl)

I felt like because it was more interactive I was more involved with it, I felt that it was easier to complete, and felt a greater motivation to get it done. (Sam)

Because we had to [physically] move things into yes or no, we definitely had to think about that because we had to agree on all the yeses that we were going to move. (Rebecca)

Our initial findings in researching the PLACE DTEL environment offer encouragement for investigating additional avenues for tangible and embodied interaction supports for learning, including the use of tokens or other manipulables that students can use to change the way the room reacts to their presence or to engage with the teacher or each other (through technologies such as low-powered Bluetooth or RFID). Other emerging technologies (such as tabletops, Arduino, and computer vision systems like Microsoft’s Kinect), also offer new avenues for investigating educational designs to support students in manipulating digital artifacts, adapting simulations, and making sense of, filtering, or navigating complex visualizations of a growing community knowledge base.

6.3 Elements of DTEL research
While our early designs were concerned with single class sessions, and testing specific forms of interaction, the more substantive design of PLACE gave us insight into how the various elements of an inquiry curriculum, situated with a DTEL environment, may interact during its enactment. To help describe the constraints in design a coherent DTEL curriculum, the following framework has been designed (Figure 37), which captures the various dynamics and their interactions. This can inform our own future work and that of others who engage this domain of research.

Figure 37: A framework for designing and evaluating DTEL research
6.3.1 Pedagogical Model.

The pedagogical model is the starting point for any DTEL inquiry design, without which the environment is merely a loose coupling of technologies and interactions. The pedagogical model determines the learning domain (e.g., Physics, World History, Architecture), the learning goals of the community, and the specific subject matter targeted by the design (e.g., Force and Motion in Physics, or the Roman Empire in World History). In our design of PLACE, the KCI model offered pedagogical principles to guide the design of the script, requiring, for example, that the students create a knowledge base that was semantically indexed to the learning goals, and that there must be collaborative activities such that students engaged with the entire domain, and used the knowledge base as a resource.

6.3.2 Script.

The script draws from the requirements of the pedagogical model in order to define the individual activities that make up the curriculum. Depending on the learning model and the goals of the curriculum, the script needs to specify three key elements: (1) The flow of activities, (2) participant roles, and (3) The distribution of materials. It’s important to note that, as shown by the double-headed arrow between the script and orchestration, that the script may be defined with some aspects that are open, or ill determined, depending on elements or conditions that only emerge during enactment (e.g., the requirement of KCI that the inquiry activities should depend on emergent community knowledge). The script defines the elements to be orchestrated, specifies any constraints or dependencies, and ultimately specifies the curriculum.
6.3.3 Orchestration.

As illustrated by the present research, orchestration is concerned with the successful enactment of DTEL curricula, and hence with managing teacher and students’ cognitive and attentional capacities. An outcome of my work is the consolidation of the various orchestrational elements down to four central themes: (1) Data mining and intelligent agents, which are central to S3; (2) Locational and physical dependencies, which allow the objects under inquiry and the products of the community’s knowledge construction to be mapped to, and mediated by, the physical learning environment; (3) Scaffolded tools and materials, which support students in engaging in the activity and with their peers; and (4) Ambient awareness and feedback, which can provide participants with a persistent view into the state of the community and its knowledge without requiring their constant attention. In S3, the last three orchestration elements (Locational and physical dependencies; Scaffolded tools and materials; and Ambient awareness and feedback), rely greatly on the capacity for data mining and intelligent agents to process where students are in the room and in the script, the relationship between students and their peers in the space, and the informational needs of each participant in relation to these other factors.

6.3.4 Enactment Transcripts.

One advantage of developing curricula within a DTEL framework is that there are many robust streams of data by which to evaluate its enactment and respond in real time. We refer to the combined data provided by these elements as the Enactment Transcript, which corresponds to the notion of “interaction logs” employed by other research in the learning sciences. By
recording user interactions (i.e., with peers, materials or the environment itself), researchers can conduct sophisticated queries to find trends or patterns in the community that might otherwise be too intensive to do manually. These queries of the enactment transcript can be done in real-time (i.e., during the enactment itself, and can result in changes or bindings to the script, determine the specific materials provided to particular students, or dictate timing and membership of group assignments.

We have articulated four elements with the potential to provide researchers with rich quantitative and qualitative data for evaluating their designs. It is important to note that these individual elements are not expected to be examined in isolation from each other, but rather that they provide multiple lenses from which to understand and evaluate a particular DTEL design. (1) **Student Interactions** can provide insight into how students individually, cooperatively, and collaboratively engage with the curriculum. This may include examining the kinds of discourse that students engage in during dyad or small group work (e.g., the negotiation tasks in PLACE.neo), or whole class discussion, the kinds of tools, representations, and artifacts students use during these activities, or student movement throughout the room. (2) **Generated Artifacts** provide concrete examples for evaluating student understanding at any single point in a curriculum, and can also provide insight into the growth of individual and community knowledge over time. (3) **Teacher Interactions** can give insight into how the orchestration of the script unfolded under real classroom conditions, and how effective the DTEL environment was in supporting the teacher in enacting desired scripted interactions. (4) **Agent Operations** give us detailed insight into how effective the DTEL environment was in responding to class patterns, and making moves that supported the class in its inquiry activities. In addition to the important
technical question of whether or not the agents worked as they were designed, the record of agent decisions can also highlight important information on how activities unfolded and the growth of the community and its ideas.

6.3.5 Learning Outcomes.

By analyzing the Enactment Transcripts, we can evaluate the enacted DTEL curriculum in terms of student learning outcomes. This is a critical step in evaluating the designed intervention. After confirming that the script was orchestrated as planned (if it wasn’t, then we might need to revise our expectations or predictions about student learning), we can analyze student artifacts and post-test gains to determine conceptual and epistemic learning gains. To some extent, the impact of our curriculum on student learning should be considered an evaluation of the underlying design. Although, given the nature of design-based research, there may still some meaningful findings about learning and instruction (i.e., that can inform future designs) even if the students do not show strong gains. We have identified three forms of learning outcomes that can be analyzed to provide insight into the effectiveness of the enacted design: (1) Conceptual Learning, which concerns what the students have learned about the targeted content domain over the course of the curriculum; (2) Epistemological Outcomes, which concern changes in student’s thinking and understanding about learning, collaboration, and the nature of the domain (3) Teacher Learning, which concerns new insights or practices, such as engagement within a knowledge community, approaches to support inquiry, and the use of technologies to orchestrate classroom activities.

6.4 Closing Thoughts and Future Research
The paper presents a substantive program of research that developed a distributed science inquiry environment that acts as an information and activity hub for orienting student learning across multiple learning contexts, classroom configurations, and scales of times. This work showed the potential impact a DTEL environment could have on student learning and classroom orchestration, even with only partial integration into students and teachers’ everyday practices.

The primary goal of the research was to define the nature of DTEL, create an extensible technology framework that could support DTEL environments, and to do so by developing a curriculum that maintained the important pedagogical and epistemic principles of collective inquiry by a knowledge community (i.e., the KCI model).

The resulting curriculum, called Physics Learning Across Contexts and Environments (PLACE) was supplemental, meaning that the teacher used the PLACE materials, activities and DTEL features periodically throughout the 12-week time of enactment (i.e., as homework, or to inform class discussion). Moving forward, of significant interest would be to develop and enact a more integrated DTEL curriculum (i.e., where the entire corpus of content and interaction would be mediated by the environment, not just as a supplemental layer), and the effects this would have on how students engage with the subject matter and their class as a knowledge community.

It is important to note that PLACE was co-designed with our partner teacher, a veteran physics teacher who collaborated with the project for several years. The teacher is exceptional, in terms of his experience with technology and innovative forms of instruction, and enjoys the advantage of an elite group of students who were eager participants in this study. The technology and curricular innovations are groundbreaking, in the sense that they represent completely new forms of learning in a unique technology-enhanced environment. However, the lack of broader
implementation or comparison studies (e.g., with a control group), limit the generalizability concerning whether the forms of learning defined and investigated in this work are actually more effective than any other approach. It was not the goal of this research to offer any such comparison. Rather it sought to articulate the notion of DTEL, and to design and enact one DTEL learning environment in the context of a specific theoretical model of collective inquiry (KCI). Hence, an interesting topic for future research would be the extension of this study's outcomes to other theoretical models and educational environments, such that student learning outcomes within the curriculum and technology can be empirically examined and compared.

Research into how “immersion” in a DTEL environment could impact student learning of content and epistemological aspects (e.g., their views of working as a knowledge community), offer compelling avenues for future research. For example, it would raise interesting questions concerning persistent, aggregated representations of community knowledge (to be used both directly as a resource, and in ambient fashion, to motivate discourse), in terms of supporting students in understanding the state of the community, their place within it, and the growth of the community’s knowledge. Research could address how such representations could help the teacher better gain insight into the state of the class’ knowledge, possible gaps in their knowledge, and in highlighting new avenues for inquiry. Such questions are currently being investigated by other DTEL researchers, using S3 as a technological foundation (Cober et al, 2012, 2013).

An important topic of investigation in this study was the role that agents can play in supporting DTEL, leading to insights about new avenues for research into data mining and intelligent agents. For example, one interesting question centers on how agents could make community
representations more context sensitive and responsive to the emergent patterns of the community’s inquiry. Another is concerned with the role that agents could play in developing “knowledge awareness” between members within a knowledge community - both in real-time and over sustained and asynchronous scales of time. Connecting students with peers who are investigating similar stands of inquiry (i.e., in order to support the sharing and building on each other’s ideas) is an ideal fit with the social constructivist models of learning. Doing so within a protracted knowledge community approach to inquiry curriculum is a challenge that can be supported by DTEL environments. Agents and data mining could play a significant role in helping to connect students to one another, draw their attention to relevant strands of research (which may not be obvious on the surface), and highlight co-presence.

Another potential avenue for future research is concerned with how to get students engaged as a persistent knowledge community within a DTEL environment, to move beyond simply recording notes and ideas and begin to foster elements of social presence within the community. Supporting such elements of a community, which move beyond simple tasks materials and grouping, is a critical challenge that entails sustained involvement and a sense of identity. These elements are clearly an area of work that remains of high concern for research surrounding education-based knowledge communities.

This research has shown that a DTEL environment can be the unifying hub for a knowledge community, and that learning can be supported across multiple locations. Technologies and frameworks such as S3 offer new ways to seamlessly integrate DTEL environments into the everyday practices of learners. Doing so requires us to think deeply about how to support students in connecting experiences from everyday life to those of school-based inquiry, and how
to connect students to the broader community and resources that may be relevant to their inquiry, including experts, data, or other networks of learners.

The expansion of the Internet of Things, and other tangible modes of interaction offer the potential for further “distributing” the learning environment into the physical learning environment and instrumenting the world around students. The use of fiducials, Arduino, RaspberryPi, RFID, and low-powered Bluetooth all offer the promise of extending the ways in which the physical and digital can interact, helping students makes sense of and manipulate the artifacts and knowledge of the community.

Finally, in developing distributed technology frameworks that can support student learning within and across environments and contexts, it is important for researchers to embrace the design-based approach to their research, adopting cycles of design, enactment, evaluation, and redesign, incorporating new findings and understandings about learning. The goal of S3 is to support a community of researchers as they develop DTEL interactions, working together as a scientific community of knowledge sharing and inquiry.
References


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APPENDICIES
APPENDIX A: Research Information Letter

To: Students of Shawn Brooks’ grade 11 science class
From: Dr. James D. Slotta
Subject: UTS teachers’ participation in a curriculum planning study at University of Toronto.

I am interested in conducting a research project in your school entitled: New Ways of Teaching and Learning in Technology Enhanced Classrooms. This project will investigate how students can help each other by creating, discussing, and solving a variety of physics examples and problems. Your physics teacher will design activities that allow you to collaborate with your classmates in small groups or take part in whole class cooperative learning. Different technologies will be used depending on the topic and type of activity. My research team, including myself and one of my doctoral students (Mike Tissenbaum), will help your teacher use the technology by providing design assistance and technical support. Example technologies are wikis, online discussion forums, Web-based learning environments, and simulations. The information provided from this study will be valuable to our research community to understand how teachers develop inquiry curriculum, and how students learn from this curriculum. It will also be of value to your school administration, in terms of promoting innovative teaching practices for your teachers.

It is important that you know that both your teacher and the school principal have approved of this study. Most research activities will involve only normal teaching practices. We will examine the teachers’ curriculum designs, observe their teaching, and ask them about their assessments of student work. Occasionally we will ask students for an interview to gain a deeper understanding of their experience of the curriculum, as well as their understanding of the topic. If you are asked to participate in an interview, we will give you and your parents a separate Interview Consent Form. We may also want to videotape certain class periods, in which event we would give a separate Video Permission Letter to all students in the class and their parents.

Because any activities associated with this project will occur as part of your regularly scheduled class, they will not require any additional effort on your part. Efforts will be made to make sure this research does not interfere with your regular learning and only improves your learning experience and your teachers’ experiences as well. Some possible activities you may participate in include: learning about and using new technologies, having discussions about math or science problems with your classmates; and participating in brief interviews with myself or my doctoral students. You may also be asked to complete a short questionnaire about certain math or science concepts at the beginning of the term so that we can assess your developing understanding. Only myself and my doctoral students will have access to any of the information collected for the study. At no time will your names, your teacher’s names, or the name of your school be identified in published
documents. All information that is collected will be kept in locked files and will be destroyed upon completion of the research.

There are no risks associated with participation in this study and you are free to withdraw from the research at any time. **Your participation in this study in no way affects your grade for the course. If you decide not to participate in the study, or if you withdraw from the study at any time, your grade will not be influenced in any way.**

Every effort will be taken to make sure your identity is kept confidential. Most of the information used in this research project will be in the form of computer-based materials used during your curriculum activities. Your identity will be visible to your classmates and your teacher, but will not be available to anyone from outside the school. Our research team will work with your materials, but will never include your name or any identifying information in any of our analyses, reports, or materials. For our own internal reference to your information, we will replace your name with a random ID number (not your student number). Any information will only be accessed from a secure database within my research laboratory. If you are asked for an interview, we will do so either before or after class, or when your teacher is not in the room. All interviews will be conducted in a private room during your lunch hour or after school.

If either you or your parents/guardians have any questions about the study please feel free to contact me by phone: 416-978-0121 or through email: jslotta@oise.utoronto.ca. Any questions about your rights as a participant can be directed to the University of Toronto Ethics Review Office at: ethics.review@utoronto.ca or 416-946-3273.

Sincerely,

James D. Slotta
Associate Professor, Department of Curriculum, Teaching and Learning, OISE/UT
Canada Research Chair in Education and Technology

**Published** study results will be made available for students and/or parents who are interested. Please feel free to contact the principal investigator with any questions or concerns: James D. Slotta, Associate Processor, OISE/UT, 252 Bloor Street West, Toronto, ON M5S 1V6. Phone: (416) 978-0121, Email: jslotta@oise.utoronto.ca
APPENDIX B: Consent for Video Recording of Student

To: Parents and/or Guardians of Shawn Brooks grade 11 physics class
From: Dr. James D. Slotta
Subject: Letter of Consent to be videotaped as part of a University of Toronto Study

This letter is requesting your permission for your child to appear in a video as part of an ongoing collaboration between our research group at The University of Toronto and the UTS science department. This project has been approved by Michaele Robertson, Principal of UTS, and by the University of Toronto Research Ethics committee.

Earlier this year, you received an information letter about the project, which we are also providing again for your reference. Essentially, it is concerned with the design of inquiry science curriculum activities for UTS students. All curriculum is designed by the teachers, in collaboration with our group.

This letter requests your permission for your child to appear in a video as part of a regular classroom observation. The video will not focus on your child specifically, but rather the classroom as a whole. The videotape will be set-up in an area of the classroom to capture the normal, everyday interactions that occur between students and the teacher. The camera will be directed only at students who have agreed to appear in a video. If a non-consenting student is interacting with a consenting student(s), the video will not take place to respect the wishes of the non-consenting student. The teacher is aware of the video recording, but will not know whether a student has agreed to appear in a video or not (in order to avoid any sense of favoritism). In no way will the video be published in any document or publicly-available information source. The willingness to appear in a video is strictly voluntary, and will provide an important source of information to our research team, including myself and a doctoral student (Mike Tissenbaum). You or your child may withdraw your consent to be videotaped at any time, if uncomfortable or inconvenienced for any reason. Video will only take place during regularly scheduled class time.

If you consent to your child appearing in a video for this study, please return the attached permission form. You will be given a copy of this form for your reference.

If you have any questions or concerns about the study, please feel free to contact me by phone: 416-978-0121 or through email: jslotta@oise.utoronto.ca. Questions about your child’s rights as participants can be directed to the Ethics Review Office at: ethics.review@utoronto.ca or 416-946-3273.

Sincerely,

James D. Slotta
Please complete and return the consent form below by [date] to your child's science teacher at UTS.

I have carefully read and understood the details of the study outlined in this letter.

Name of Student (please print)                                      Name of Parent/Guardian (please print)

______________________________________  ______________________________________

Student’s Signature                                                          Parent/Guardian’s Signature

______________________________________  ______________________________________

Date

Published study results will be made available for students and/or parents who are interested. Please contact the principal investigator by phone at: (416) 978-0121 Email: jslotta@oise.utoronto.ca. Any questions about teachers’ or students’ rights as participants can be directed to the University of Toronto Ethics Review Office at: ethics.review@utoronto.ca or 416-946-3273. Research results will be made available upon request.
APPENDIX C: Student Interview Consent Form

To: Parents and/or Guardians of Shawn Brooks grade 11 physics class
From: Dr. James D. Slotta
Subject: Letter of Consent to be interviewed as part of a University of Toronto Study

This letter is requesting your permission for your child to be interviewed as part of an ongoing collaboration between our research group at The University of Toronto and the UTS science department. This project has been approved by Michaele Robertson, Principal of UTS, and by the University of Toronto Research Ethics committee.

Earlier this year, you received an information letter about the project, which we are also providing again for your reference. Essentially, it is concerned with the design of inquiry science curriculum activities for UTS students. All curriculum is designed by the teachers, in collaboration with our group.

This letter requests your permission to interview your child about his or her experience with those activities: Were they enjoyable? Were they an effective way to learn? Did they help classmates collaborate with one another? The interview itself will have no impact on your child's grade. The teacher is aware that interviews are happening, but will not know the identities of student being interviewed (in order to avoid any sense of favoritism).

This interview is strictly voluntary, and will provide an important source of information to our research team, including myself and a doctoral student (Mike Tissenbaum). Your child is free to withdraw from the interview at any time, if uncomfortable or inconvenienced for any reason. Interviews will last approximately 10-15 minutes, and will be conducted between classes or immediately after school. You are receiving this letter because your child volunteered to be interviewed, although your permission is required before the interview can take place.

If you consent to your child participating in an interview for this study, please return the attached permission form. You will be given a copy of this form for your reference.

If you have any questions or concerns about the study, please feel free to contact me by phone: 416-978-0121 or through email: jslotta@oise.utoronto.ca. Questions about your child’s rights as participants can be directed to the Ethics Review Office at: ethics.review@utoronto.ca or 416-946-3273.

Sincerely,

James D. Slotta
Associate Professor, Department of Curriculum, Teaching and Learning, OISE/UT
Canada Research Chair in Education and Technology
Please complete and return the consent form below by [date] to your child’s science teacher at UTS.

I have carefully read and understood the details of the study outlined in this letter.

___________________________  ______________________________
Name of Student (please print)  Name of Parent/Guardian (please print)

___________________________  ______________________________
Student’s Signature            Parent/Guardian’s Signature

___________________________
Date

Published study results will be made available for students and/or parents who are interested. Please contact the principal investigator by phone at: (416) 978-0121 Email: jslotta@oise.utoronto.ca. Any questions about teachers’ or students’ rights as participants can be directed to the University of Toronto Ethics Review Office at: ethics.review@utoronto.ca or 416-946-3273. Research results will be made available upon request.
APPENDIX D: UTS Parent and/or Guardian Video/Photograph Consent Letter

To: Parents and/or Guardians of [Teacher’s name] grade [#] science class
From: Dr. James D. Slotta
Subject: Letter of Consent to be videotaped/photographed as part of a University of Toronto Study

This letter is requesting your permission for your child to appear in a video and/or photographs as part of an ongoing collaboration between our research group at The University of Toronto and the UTS science department. This project has been approved by Rosemary Evans, Principal of UTS, and by the University of Toronto Research Ethics committee.

Earlier this year, you received an information letter about the project, which we are also providing again for your reference. Essentially, it is concerned with the design of inquiry science curriculum activities for UTS students. All curriculum is designed by the teachers, in collaboration with our group.

This letter requests your permission for your child to appear in a video and/or photographs as part of a regular classroom observation. The video/photos will not focus on your child specifically, but rather the classroom as a whole. The cameras will be set-up in an area of the classroom to capture the normal, everyday interactions that occur between students and the teacher. The cameras will be directed only at students who have agreed to appear in a video and/or photographs. If a non-consenting student is interacting with a consenting student(s), the video/photos will not take place to respect the wishes of the non-consenting student. The teacher is aware of the recording, but will not know whether a student has agreed to appear in a video/photos or not (in order to avoid any sense of favoritism). The willingness to appear in a video and/or photos is strictly voluntary, and will provide an important source of information to our research team, including myself and two doctoral students (Mike Tissenbaum and Michelle Lui). You or your child may withdraw your consent to be videotaped at any time, if uncomfortable or inconvenienced for any reason. Video/photos will only take place during regularly scheduled class time. You are receiving this letter because your child indicated a willingness to appear in a video/photos, however, your permission is required before any recording can take place.

There are several options for you to consider if you grant permission for your child to take part in this research. You can choose all, some or none of them. Please put a check mark on the corresponding line(s) that grants me your permission to be videotaped and/or photographed:

I grant permission to be videotaped: Yes: ___ No: ___
I grant permission to be photographed: Yes: ___ No: ___

Please put a check mark on the corresponding line(s) that grants me your permission to use the
I grant permission to use the videos/photos as raw data for coding and analysis (video will not be shown publically)  
Yes: ___ No: ___

I grant permission to use the videos/photos in presentations in classrooms or conferences  
Yes: ___ No: ___

I grant permission to use the video in other types of promotional video, such as posting on our project Web site  
Yes: ___ No: ___

If you consent to your child appearing in a video and/or photographs for this study, please return the attached permission form. You will be given a copy of this form for your reference. If you have any questions or concerns about the study, please feel free to contact me by phone: 416-978-0121 or through email: jslotta@oise.utoronto.ca. Questions about your child’s rights as participants can be directed to the Ethics Review Office at: ethics.review@utoronto.ca or 416-946-3273.

Sincerely,

James D. Slotta
Associate Professor, Department of Curriculum, Teaching and Learning, OISE/UT Canada
Research Chair in Education and Technology

Please complete and return the consent form below by [date] to your child’s science teacher at UTS. I have carefully read and understood the details of the study outlined in this letter.

_________________________________  __________________________________
Name of Student (please print)  Name of Parent/Guardian (please print)

_________________________________  __________________________________
Student’s Signature  Parent/Guardian’s Signature

________________________________
Date

Published study results will be made available for students and/or parents who are interested. Please contact the principal investigator by phone at: (416) 978-0121 Email: jslotta@oise.utoronto.ca. Any questions about teachers’ or students’ rights as participants can be
directed to the University of Toronto Ethics Review Office at: ethics.review@utoronto.ca or 416-946-3273. Research results will be made available upon request.
APPENDIX E: Teacher Consent Letter

To: Shawn Brooks
From: Dr. James D. Slotta, Associate Professor, OISE/University of Toronto
Subject: Letter of Consent to Participate in University of Toronto Study

I am interested in conducting a research project in your class this year entitled *New Ways of Teaching and Learning in Technology Enhanced Classrooms*. As part of a research project, I am interested in how teachers can use technology in their classrooms to help students’ understanding of science. Specifically, my research team would collaborate with you and your colleagues to design a collaborative curriculum where students interact deeply with peers in rich inquiry activities. The information that this study generates will aid in finding new and perhaps better ways for teachers to help students develop deep understandings about science.

This study provides a unique opportunity for students in your class to experience an innovative approach to science learning that utilizes technology and aligns with new curriculum standards. Consenting students in your grade 11 science class will be participating in the study. The students would be participating in the study during regularly scheduled class time. Every attempt will be made to ensure that the study does not impede any of the regular course instruction and will enrich the students’ learning experiences. Occasionally, myself or one of my doctoral students (Mike Tissenbaum) might need to interview students after school or during their regular lunch hour. As a participating teacher, you may also be asked to participate in an interview before, during, or after the study. It is important that you know that participation in this activity is strictly voluntary and you and/or your students may withdraw from the study at any time, for any reason, and without penalty.

Some of the things the students would do during the study are: learning about and using new technologies, having discussions about science with their classmates; and participating in brief interviews with one of my doctoral students or myself. Students may also be asked to complete a short questionnaire about science at the beginning and end of the study so that any changes in their level of understanding can be measured. All information collected during the study will be used for the purposes of data analysis. Only my doctoral students and myself will have access to any of the data that is collected for the study. At no time will students’ names, your name, or the name of your school be identified in published documents. All information that is collected will be kept in locked files and will be destroyed after the research is completed. There are no risks associated with participation in this study and students’ grades will not be affected by choosing to participate.

Procedures will be taken to ensure the identities of participating and non-participating students remain confidential during all phases of the study. Most of the information used in this study will be from the computer-based data logs. This information will only be accessed from my or my doctoral students’ own private computer. You will not know which students have decided to participate in the study by reviewing any of the students’ work. Information will be reviewed only from those students who are participating in the study. Any written data (e.g. quizzes) will be collected from the entire class. In private, a photocopy will be made only of the work.
completed by participating students. If a student is asked for an interview, they will be asked either before or after class, or when their teacher is not in the room. Interviews will take place either during lunch hour or after school. At no time will you know whether or not a student has decided to participate in the study.

A copy of this consent form will be given to you for your reference. If you have any questions about the study please feel free to contact me by phone: 416-978-0121 or through email: jslotta@oise.utoronto.ca. Questions about students’ rights as participants can be directed to the University of Toronto Ethics Review Office at: ethics.review@utoronto.ca or 416-946-3273. Research results will be made available upon request.

Sincerely,

James D. Slotta
Associate Professor, Department of Curriculum, Teaching and Learning, OISE/UT
Canada Research Chair in Education and Technology

I give my permission for Dr. James D. Slotta to conduct the research project outlined above.

________________________________
Signature

________________________________
Date

Published study results will be made available for students and/or parents who are interested. Please feel free to contact the principal investigator with any questions or concerns: James D. Slotta, Associate Processor. OISE/UT, 252 Bloor Street West, Toronto, ON M5S 1V6. Phone: (416) 923-6641 Ext. 2446, Email: jslotta@oise.utoronto.ca
APPENDIX F: Student Pre-Post-Unit Questionnaire

Please enter your first and last name:
Gender: * Female _____ Male _____

**Section 1: Physics and the real world**
Note: Please focus on the physics principles and theories behind the answers - and not just the numbers!

1. A bicyclist notices that he is approaching a steep hill rising in the distance. Explain, in terms of energy, why the bicyclist pedals hard to gain as much speed as possible on level road before reaching the hill?
   
   b. Another example of this sort of behavior would be?

2. Use Newton’s first law to explain why the TTC has so many handles, posts, and bars inside the subway cars.

3. Why is it important to understand the principles of physics, and not just to know the formulas and when to use them?

**Section 2: Why and How we learn science at school**
Just answer to the best of your knowledge – these are a survey of your opinion only (not graded)

1. How would you rate your own performance in high school science classes you have taken:
   Circle one: [ Poor, Average, Good, Excellent ]

2. How do you know when you understand something? How can you tell:

3. "Overall, the science I learn in school has little or nothing to do with my life outside of school."
   Circle one: [ Agree Disagree ] Please explain:

4. When learning new science material I prefer to:
   Put an “x” under one column for each statement: Most of the times Sometimes Rarely
   
   Be told what is correct by a teacher.
   Read a full explanation in the textbook.
   Have an expert explain it to me.
   Do experiments, make observations and try to figure things out (either by myself or with others)
   Use what I already know to understand new material.
   Use an example to help me understand new ideas.
   Discuss with my peers to work out the answer together

4. Describe a situation where learning science was enjoyable and effective for you:

6. In S3 physics:

   I get the chance to talk to other students.
I talk with other students about how to solve problems.
I explain my ideas to other students.
I ask other students to explain their ideas.
Other students listen carefully to my ideas.

7. What is your opinion of working with your peers:

<table>
<thead>
<tr>
<th>Agree</th>
<th>Neutral</th>
<th>Disagree</th>
</tr>
</thead>
</table>
I enjoy working with my peers.
Compared with working individually, working with others allows me to tackle more complex project topics.
Giving and receiving feedback amongst peers is an effective way to help resolve misconceptions about physics.
I learn more effectively by working with peers on a project than by doing homework.
Working with peers is fine for some classes, but its better not to learn that way in science.

8. What is your opinion about technology and learning:

<table>
<thead>
<tr>
<th>Agree</th>
<th>Neutral</th>
<th>Disagree</th>
</tr>
</thead>
</table>
I regularly use my computer when completing work for class.
I use technology-based communications (e-mail, chat, cell phones, SMS) more often than face-to-face communication to discuss school work with my peers.
I use online tools like text messaging, facebook or other methods to complete school projects.
Outside of class I visit “social media” Web sites (Facebook, YouTube, etc).
Technology is an effective means for negotiating ideas
Presented information in multiple formats (text, video, visualizations) makes it easier to understand.

** Section 3: The PLACE Web and Smartroom activities **

9. Did you find that the Smart Classroom Hollywood Physics activity connected to the overall content of the course (including the earlier PLACE activities)? If so, please provide concrete examples, or if not, why you think it didn’t.

10. Please describe your feelings about the Smart Classroom activity (feel free to discuss both as an experience and it’s connection to the Physics course)

Any other comments?
APPENDIX G: Teacher Pre-Unit Interview

1) In previous years during the Force and Mechanics units what kinds of conceptual problems have students tended to encounter?
   a. How would you describe the goal of this experimental intervention?
   b. What kinds of interactions with students would you like to engage in?
   c. What information would you need to engage in such interactions?

2) How could seeing students’ individual responses to homework problems online help you in preparing for the following day’s class activities?

3) How do you think the ability to see students’ reasoning about physics principles relating to their submitted artifacts (like their examples) could help you in preparing upcoming lessons?
   a. What kinds of insights could this provide you?

4) How will the PLACE.Web site provide information about students’ engagement in the course and with course materials?

5) How could the combined visualization of Homework and student generated artifacts provide you with insights into the state of knowledge in the class?

6) How could technology like PLACE.Web enrich students’ experience with the curriculum?

7) Will using a system like PLACE.Web, with its focus on principles and explanations, change the way you approach the rest of the curriculum? How so?

8) What are your concerns about implementing this technology?
APPENDIX H: Teacher Exit Interview

1. What, in your own words, do you think this study was about?

2. What were some of the most interesting or positive aspects of this study for you personally?

3. How did the various technologies in PLACE influence your interactions with students?
   - The PLACE.Web?
   - The Homeworks/Examples?
   - The smart classroom?

4. PLACE.Web was designed to help students make connections between the physics in the classroom and life outside school. How do you feel it succeed in this?
   b) What were any problems?

5. PLACE.Web, including the homework/Example tasks, were organized to help students pay attention to the core physics principles. How well do you think this worked?
   b) What were some of the ways you saw this strategy paying off?
   c) What were some of the limitations?

6. Could you give your thoughts on each of the following technologies/activities:
   - PLACE (the visualization)
   - The student created examples
   - Student created challenge problems
   - Homework

7. What were the best aspects of the smart classroom from your standpoint?

8. What would you like to see more of?

9. How did the smartroom offer you new ways to interact with students?

10. What information were you paying the most attention to from the various technologies?

11. What ideas do you have for extending/improving the technology and/or the smart classroom activity?

12. How do these kinds of social and interactive curriculum activities change the way that students learn about physics?
    b) Do you feel they learn better, deeper, differently?
    c) If so how?
APPENDIX I: Student Exit-Interview

1. In your own words can you describe the smart classroom activity?

2. What do you think was the goal of the activity?

3. Can you recall any moments in the activity that stood out to you, as particularly fun? Interesting?

4. Do you feel like you got any insights or understanding from the activity?

5. Any parts of it you remember being challenging, or frustrating?

6. How effective were the tablets in providing you instructions, in helping you do your assigned tasks? What did you think about the “smoothness” of the interactions on the tablet (swiping, clicking on objects)?

7. What were your feelings about the individual wall display that showed the videos, and your work? Do you remember how your team would “negotiate” - each using your tablets? Any reflections about that process? Was that the first time you’ve ever had 3 or 4 friends driving the same screen?

8. Did Shawn ever engage with you while you were doing your work? What did he talk with you about? Do you remember if he looked at your tablets or the large display to facilitate this discussion?

9. What do you remember about the display at the front of the room that showed where you were in the classroom and flashed time warnings? Did you find yourself looking at it at all? If so when/why?

10. Do you remember how you felt when the room “sorted you” (told you where to go in the room, as shown on your tablet, and the ambient display)?

11. When you got to your final board (the one where you ultimately set up the physics problem and recorded video of your solution) – you found some equations that had been left by the preceding group, and then you made assumptions, etc. Did this board help you as you were thinking about the problem solution?

12. Did your overall experience, with in the room, affect your motivation in completing the task? Was there anything inspiring about the fact that it was happening in 4 different groups around the room?

13. What about the future of learning in classrooms? Is there anything from this experience that you feel might be relevant to the design of “smart classrooms” in the future (and the learning activities that happen in them)?
14. Are there any other comments about the activity that you’d like to share?