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Co-Designing Collaborative Smart Classroom Curriculum for Secondary School Science

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Abstract: This paper introduces a series of iterative designs that investigate how the aggregation and visualization of student-contributed work can support collaborative problem solving in the domain of physics. We investigate how new technologies can enable students to contribute to a shared knowledge base, working across contexts: in class, at home, and in a specialized “smart classroom” environment. We explore how student data can be provided to the teacher *before* class, in support of planning the next day’s lesson, and *during* class, to help the teacher orchestrate class activities and respond to student needs. Our work builds upon the research tradition of knowledge communities and inquiry learning to inform its design of materials and activities that support productive collaborative interactions for learners. We are also guided by the recent literature on scripting and orchestration to define curricular activities that bridge home and school environments, leveraging a digital platform that includes Web 2.0 features to guide structured collaborations. This paper reports on a design-based research program in which the development of the curriculum and technology platform is informed by successive cycles of design, enactment, analysis, and re-design. The paper will review our efforts through three successive design cycles, exploring the evolution of our own “smart classroom curriculum” for high school physics. For each iteration, we present our design goals, the resulting curriculum and technology, the student learning outcomes, and our evaluation that informs the next iteration. We end with a description of our current design, and discuss the goals and directions of our future efforts.

Keywords: Future Classrooms, Science Education, Physics, Collaborative Inquiry
Categories: L.3.6, L.6.2, L.3.0, L.2.3, L.1.0

1 Introduction

As society moves further into the "Knowledge Age," everyday workplace practices are being increasingly changed and shaped by new and advancing technologies [Zuboff, 1988]. In general, the daily practices of individuals in the modern workplace are increasingly more data-driven, collaborative, and dependent on a set of fundamental skills commonly referred to as information literacies or digital literacies

[Livingstone, 2008]. This shift has been particularly pronounced across the STEM (Science, Technology, Engineering, and Mathematics) disciplines, where data-intensive practices of the 21st century have moved from individual scientists, or small groups of scientists, working with separate databases and computational simulations, toward large multi-user databases, requiring multidisciplinary collaborations and data mining skills across ever-widening spatial and temporal scales [Gray & Szalay, 2007]. This shift in the skills and practices highlights the need to integrate such practices into students' learning of STEM content, or we risk seriously hindering students' future success in related careers [NSF, 2008].

Despite the growing need to integrate technology and knowledge society skills into daily classroom activities, their adoption still lags far behind students' engagement with them outside of school [Buckingham, 2007; Collins and Halverson, 2010]. The emergence of Web 2.0 technologies, such as YouTube, Facebook, and Wikipedia engage students in the creation of new digital media, collaboration with peers, and contribution to social and semantic networks [Slotta, 2010]. Further, the arrival of mobile technologies such as smartphones has added a sense of the ubiquitous nature of learning and computing. Thus, the forms of learning and engagement in which students actively participate outside the classroom typically involve the collaborative construction of materials, social networking, and ubiquitous approaches that characterize our descriptions of 21st century knowledge skills.

It is thus compelling to investigate K-12 learning activities and environments where the production and aggregation of content emerges from the collective contributions of all members of the community, rather than from a single authoritative source. Subsequent instructional activities could actively engage students in using such content, continually applying and refining their collective knowledge as a central goal or outcome of the instruction. Such "socially-oriented" models of classroom instruction [Ullrich et al., 2008] can enable students to take more active roles in the classroom environment and become creative producers of their own curriculum content [Buckingham 2007; Ito et al., 2009]. Another feature of socially constructed content is users' ability to create taxonomies or "folksonomies," which are emergent, user-defined metadata that can be used to sort and connect data in ways that are relevant to those interacting with it [Al-Khalifa & Davis, 2006]. These are particularly promising for educational applications, as they can enable any users – not just experts – to participate in, and learn from their own patterns of participation [Mathes, 2004]. The connections made by students using such tagging systems could also provide the opportunity for varied representations and visualizations of the data, which has been shown to complement inquiry learning practices [Krajcik et al., 1998].

The dynamic aggregation and representation of student contributed content can also provide "real-time" insight into the state of knowledge within the classroom across a variety of contexts (i.e., formal and informal learning environments) and configurations (i.e., individual, small group, or whole class interactions). Access to these representations during class time, could provide teachers with new opportunities for orchestrating classroom activities [Lui, Tissenbaum & Slotta, 2011]. Early efforts at aggregating student responses, such as ConcepTest (Mazur, 1997), where students employ Audience Response Systems ("Clickers") to provide a summative view of their collective responses to multiple-choice items, have been shown to highlight student misconceptions in the domain of Physics [Crouch & Mazur, 2001]. However, discourse among students in such applications is limited, and the insight about student reasoning is not readily available to teachers or to students. Nonetheless, some projects have made effective use of aggregating information about student problem solving in order to provide teachers with on-the-fly assessments of student work that informs their orchestration of classroom activities [Rodriguez et al, 2010].

This paper presents research that expands on the kinds of information available to both students and teachers alike by capturing, not only student responses to problems, but also their written reflections and explanations of their responses. Access to this aggregated data provides students with opportunities to build personally relevant understandings of the curriculum [Bransford et al., 1999; Krajcik et al., 2008; Linn and Eylon, 2006]. For teachers, this data provides a rich source of evidence about the state of student knowledge, allowing them to respond to any evident misconceptions and help students develop a deep understanding of curriculum topics [Dillenbourg & Jermann, 2007]. Another important goal of this work is to extend the learning activities beyond the normal bounds of classroom instruction, introducing activities outside of the traditional classroom to augment the aggregation and representation of student ideas. By allowing students to access such content as part of homework activities, we can free up class time for focused knowledge building activities led by the teacher who uses the aggregate information to aid in his or her scripting of the lesson.

Our general goal is to investigate rich new forms of learning and instruction where students contribute their own ideas and content materials, creating a semantic network that informs a variety of pedagogical applications. Another goal is to bridge the gap between technology and pedagogy in the development of learning spaces that harness technology providing new opportunities for students and teachers alike. In order to progress in such research, we have developed an open source "smart classroom" technological infrastructure that serves to capture and aggregate student contributions, and helps orchestrate their collaborative activities both inside and outside the classroom [Tissenbaum & Slotta, 2009; Slotta, 2010; Lui, Slotta & Tissenbaum, 2011].

In sections below, we describe a design-oriented study of student learning and problem solving in physics. We describe both the technological and pedagogical developments, which serve to advance our goals of enabling students and instructors to learn together as a community. Within the research literature on learning and reasoning in physics, much work has been done to investigate the nature of novice-expert differences [Chi, Feltovich and Glaser, 1981; Priest and Lindsay, 1992, Slotta, Chi, & Joram, 1995], self-explanation [Chi, et al., 1989; Nokes, Schunn, & Chi, 2010], the nature of misconceptions [Reiner, Slotta, Chi and Resnick, 2000] and other phenomena. Here, we consider the possible benefits of collective inquiry and socially aggregated representations for learning in physics, focusing on three dimensions: First, the aggregation and display of student ideas for purposes of reflection and development of understanding; second, a focus on principles as an organizational framework to guide physics learning; finally, new opportunities for the teacher, in response the products of such aggregated student ideas (i.e., in responding to students, selecting follow-up questions or materials, or monitoring the level of understanding within the classroom community).

2 Literature Review

2.1 21st Century Learning Skills for the "Knowledge Age"

Over the past three decades, society as a whole has shifted away from the longstanding focus on work and knowledge as means to material ends (the hallmarks of the industrial age) toward a "knowledge society" in which knowledge is valued as an end itself, and seen as the means for producing greater knowledge [Glibert, 2007; Bereiter & Scardamalia, 2005]. Businesses are beginning to understand the changing nature of the workplace, but schools have been slow to change their fundamental commitments from a model of learning that is based largely on the needs of industrial preparedness [Hargreaves, 2003]. Today's classrooms are still dominated by a "knowledge transmission model" in which lectures, textbooks, and graded assessments still constitute the vast majority of curricular content [Laurillard, 2002]. Even the constructivist perspectives of the late 20th century, which call for a focus on critical thinking, inquiry and argumentation [e.g., Krajcik et al., 2008; Linn and Eylon, 2006], are largely cast at the individual level of learner, with little attention paid to the development of a collective or social epistemology. Recently, educational researchers have acknowledged that a "knowledge community" approach to learning and instruction may be better suited to the needs of modern society, where individuals typically collaborate, solve novel problems, create and share knowledge, and synthesize from multiple sources [Brown & Campione, 1996; Slotta & Najafi, 2010].

In order for students to develop such skills, it may be important to change the nature of the learning environments such that classroom instruction places less emphasis on treating all students as parallel individual learners, and responds to them rather as a unified whole. Today's classrooms must respond to individual students' interests, strengths, experience and needs, supporting a classroom community through cooperation, shared responsibility, and respect. Curriculum must be developed that provides challenging opportunities for all students to learn and engage in STEM activities and develop 21st century knowledge skills [Partnership for 21st Century Skills, 2007].

2.2 Emergence of Web 2.0: Technologies for Collaborative Inquiry and Knowledge Communities

Outside of school, students' online activities are increasingly centered around the social Web, or Web 2.0. Web 2.0 is generally described as a group of technologies, such as Flickr, YouTube, Facebook, social bookmarking services, which at their core facilitate a more socially connected Web where the members are responsible for development, distribution, and assessment of the content within the community [Andersen, 2007]. In this way the content, and by extension the community that drives it can draw from the "wisdom of the crowd" to better respond more deeply to the needs of its users [Alexander, 2006]. Andersen [2007] describes six key features of a successful Web 2.0 community as: (1) promoting individual production and user generated content; (2) the ability to harness the power of the crowd; (3) the collection and creation of data on a large scale; (4) the fostering and development of an architecture of participation; (5) the "Network Effect", wherein the benefit that users derive from the system increases with the growth of the community; and (6) supporting and fostering "Openness" within the community. These elements mirror the need for generating, communicating, and collaboratively negotiating knowledge that are the cornerstones of effective organizations in today's knowledge society. They also serve as helpful design guidelines for our efforts to engage students in the production and sharing of knowledge in the classroom.

2.2.1 Meta-Data and Tagging

Due to the huge amount of information that is produced and disseminated within a collective knowledge community (thanks in part to the Network Effect), there is a need to connect disparate but related pieces of information in ways that create meaning and value to users. Assigning meta-data, or tags, to individual content is one of the most common ways of making these connections [Mathes, 2004; Wiley, 2000]. Socially constructed meta-data is particularly powerful in Web 2.0 environments as it allows users to individually assign descriptors to a piece of content (i.e., a website, a video, a picture, a reflection) without having to know about every other piece of content that shares the assigned attribute. Users can rely on the computational power of the underlying database to sort the collection of tags, resulting in meaningful connections and increased usefulness of the content [Hayman & Lothian, 2007].

The types of tags employed for semantically labeling content can be broken down into two distinct, although sometimes intersecting approaches: Taxonomies and Folksonomies. A taxonomy is a top-down approach that employs domain specific vocabulary and is often created by the organizer of the content repository, a domain expert, or some other authoritative source [Al-Khalifa & Davis, 2006], where as a folksonomy draws its keywords for classification from the community itself in a more ad-hoc or grassroots approach [Alexander, 2006; Mathes, 2004].

Because of folksonomy's ground up approach and consequent ability to capture unanticipated values of the user community, it has been of great interest to researchers [see for example, Plangprasopchok, Lerman & Getoor, 2010; Anderson & Whitelock, 2004]. However this openness can result in significant challenges for its applicability for certain learning contexts [Hsieh, Lai, & Chou, 2006]. Most notably, because of their unstructured nature, the meta-data created by users can be messy, imprecise, inaccurate, and ambiguous [Guy & Tonkin, 2006]. Furthermore, folksonomy tags are inherently personal in nature, rather than a consensual product of the community [Hayman & Lothian, 2007]. Thus, the use of identical tags by two or more different users may not imply that those users are actually ascribing the same meaning to the tagged content. Use of nominal tags (e.g., "Toronto" or "chocolate") would more likely indicate a fairly high level of shared meaning, whereas more categorical tags (e.g., "education", "nutrition") or value-oriented ones (e.g., "good,“ "useful") could simply reflect that users hold different meanings for those common words.

Although folksonomies work well for huge data sets (e.g., YouTube or Flickr), they may be difficult or impossible to apply within a classroom setting, where the number of participants is relatively small. Folksonomies, which reflect student-held ideas and values, may also pose serious challenges if the educational goal is for the community to begin understanding and using the language and classifications of experts and professionals (e.g., in the classification activities of Chi, Feltovich and Glaser, 1981). Moreover, the clutter of many tags could act as "noise," hindering students from making meaningful connections between content elements that are relevant for learning [Marinho, Buza & Schimdt-Thieme, 2008]. For these reasons, many educators have elected to refrain from the use of folksonomies in their use of student-generated content repositories. At the very least, there is an interesting tension between the productive focus on relevant semantic features that can be gained through the use of structured taxonomies and the personal and social relevance that derives from an organic, socially constructed folksonomy.

2.2.2 Student-generated Content: New opportunities for Curriculum and Assessment

The underlying technologies of these technology-supported learning environments allow for the rapid aggregation and display of student information on-the-fly [Shirley et al., 2011] in ways that simply could not be achieved in traditional pen and paper learning environments. This aggregation of student work can help both teachers and students to see the patterns of the whole class [Tatar, Roschelle, Vahey, & Penuel, 2003] towards engaging them in deeper class discussions around the curriculum and addressing student misconceptions in a more timely manner [Hake, 1998].

A prominent example of this kind of approach is that of Peer Instruction (PI), where students answer to multiple-choice “clicker” style physics problems and answers are aggregated and displayed to students as a basis for small group discussion [Mazur, 1997]. In this way, students are given a snapshot of the thinking of their peers as a way to highlight differences in their conceptualizations of the curriculum [Crouch & Mazur, 2001]. Teachers in these classrooms selectively monitor class discussions by walking around during discussion periods [Crouch et al., 2007]. While effective, there are opportunities to provide teachers with a more complete picture of individual student and small group understanding by structuring activities so students are not simply providing answers to multiple choice questions, but are also tasked with giving explicit rationales for their answers. Such rationales are arguably the greatest source of insight into student understandings [Hestenes et al., 1992], and are a powerful tool for students in generating personal meaning [Ash et al., 2005].

A similar approach can be seen in the Eduinnova project, where in teams, students solve problems sent to them on PDAs by the teacher, who then receives information back in real-time about student performance on their device [Zurita & Nussbaum, 2004]. In Eduinnova the teacher is provided with a color-coded matrix for an at-a-glance visual overview of the state of individual students’ progress within an activity, allowing them to better understand which students need immediate guidance. Although the two projects deal with the collected student information differently – PI by aggregating the whole class and Eduinova focusing on students individually - both approaches highlight new ways to gain insight into the state of understanding within a classroom setting in real-time. Furthermore, these studies show how networked technologies can allow information to move rapidly across the learning environment for display in ways customized for the specific information needs of its recipients.

A central goal of this research is to continue to advance the approaches presented above. In understanding how different forms of technology can address the informational needs of students towards making sense of their own work in relation to their peers, and for teachers in gaining and understanding the state of knowledge of their students in real-time to capitalize on opportunities for student inquiry and knowledge building.

2.2.3 Learning through Knowledge Communities, Inquiry, and Reflection

The emerging social and collaborative technologies described above are well suited to a tradition in the learning sciences described as a “learning communities” approach [Bielaczyk & Collins, 1999], or a “knowledge community approach” [Slotta and Najafi, 2010; Peters & Slotta, 2010]. Characteristics of this theoretical perspective are the promotion of a collective epistemology, where students build upon the ideas of their peers, advancing the community as a whole, a shared knowledge base, and the emergence of characteristic practices and patterns of discourse. One prominent example is seen in the Fostering Communities of Learners project [Brown and Campione, 1996], where students are orchestrated according to a complex pedagogical “jigsaw” design, distributing their expertise, sharing through “cross talk” and applying the products of their community discourse to some “consequential task” [Bielaczyk & Collins, 1999].

Another example being actively pursued by a community of researchers is called Knowledge Building [Scardamalia & Bereiter, 1996; Scardamalia, 2002], where students must assume “collective cognitive responsibility” for the advancement of their community’s knowledge with the help of scaffolding technologies [Hakkarainen, 2003].

In response to the challenges of implementing a knowledge community approach, particularly at the secondary science level, we have been investigating a new model called Knowledge Community and Inquiry (KCI) where the collective patterns of knowledge work within the community are blended with structured inquiry activities, including pedagogical and technological scaffolding [Slotta and Peters, 2008]. The research tradition of scaffolded inquiry has shown the efficacy of engaging students in activities where they are challenged to reflect, and connect ideas actively during the course of “inquiry projects” [Linn, Husic, Slotta & Tinker, 2007; Slotta & Linn, 2009]. By combining the concepts of knowledge community with scaffolded inquiry, KCI aims to focus the knowledge construction towards specific curriculum learning objectives [Peters & Slotta, 2010].

An important dynamic within any successful inquiry or knowledge community curriculum is that of reflection, which is ideally embedded within student learning activities [Bielaczyc & Collins, 2006, Slotta & Linn, 2009]. While generally accepted to be an essential part of the learning process [Engestrom, 1987; Baird et al., 1991; Davis, 1998; Ash et al, 2005], it takes on particular significance in digitally mediated learning environments [Sorensen, 1999; Johnson & Aragon, 2003]. In such environments students interact with the content and with each other asynchronously, which can provide students with more opportunities to critically think about the information at hand before placing their own ideas in the public discourse [Garrison, 2003]. Perhaps more importantly, the act of putting ideas into words within a public discourse can provide a metacognitive layer [Sorensen, 1999]. Roscoe and Chi [2007], observed that by posting ideas and responding to those of their peers, students can recognize and reconcile gaps in their knowledge.

2.2.4 Smart Classrooms for Knowledge Communities

In order to support investigations of such complex pedagogical forms, the research community is making progress on a new generation of technology enhanced learning environments [Slotta, Tissenbaum & Lui, 2011]. These advances include the ability to engage students with rich multimedia environments, the automatic collection and data mining of prior student work (e.g., through the use of intelligent digital agents), and visualizations of those products that are sensitive to the needs of their recipients [Lui, Tissenbaum & Slotta, 2011]. One goal of the present research is to investigate how a "Smart Classroom" environment [Slotta, 2010] can scaffold students in giving and receiving information within their community and in achieving learning goals.

Smart classrooms offer an expanded perspective of learning environments, in terms of pedagogical, spatial and semantic "spaces," supporting complex designs that include mappings to the physical space (i.e., different things happen at different locations within the room), logical conditions for the delivery of materials (e.g., students are provided with certain kinds of physics problems until the specified number of problems have been solved), interaction patterns (e.g., students working within a group could perform different functional tasks, each on his or her own laptop computer, with the synthesis of their efforts shown on a large projected display – providing feedback for subsequent individual actions). Intelligent agents can operate on student contributions, as well as semantic metadata, allowing an increased level of sophistication and intelligence [Slotta, 2010].

Smart classroom technologies allow the community to negotiate meaning, expand, elaborate, and challenge the ideas of their peers [Garrison, 2003]. This ability to socially negotiate and build upon the products of one's peers mirrors the ideals of Vygotsky's [1978] Zone of Proximal Development (ZPD) by providing the conduit through which students can gain a higher level of understanding by discussing the concepts under investigation with peers who are concurrently engaged with the same materials [Nicol & Boyle, 2003]. However, it should be noted some characteristics of social negotiation could be lost in environments that are entirely digital. The lack of direct face-to-face communication can limit the ability of students to draw from non-verbal cues during negotiation and discussion in addition to the kinds of dynamic discourse that in-person real-time interaction can provide [Johnson & Aragon, 2003]. Furthermore, the teacher's role as an expert guide in the knowledge construction process can be potentially hindered by limiting their ability to interject at key moments [Tissenbaum, 2011]. It is thus attractive to pursue a hybrid approach in which knowledge construction and discourse happen in virtual learning spaces, as well as in formal and informal learning spaces where students may be able to access their collective resources. The same technology infrastructure can operate "behind the scenes" of all these contexts, allowing aggregation and systems intelligence to be integrated throughout the learning experience.

2.2.5 Insight into Student Understanding

Prior research in science education has shown that novices display misconceptions in their explanations of various concepts and phenomena, and that deep understanding of certain physics concepts can be quite challenging [Chi, 2005; Slotta & Chi, 2006; Trowbridge & McDermott, 1980]. This is partly because novices enter into instruction with a well-defined knowledge base that they have derived from their everyday experiences rather than from more rigorous theory-based approaches [Reiner, Slotta, Chi & Resnik, 2000; Trowbridge & McDermott, 1980].

These prior conceptualizations reveal themselves in differences between how experts and novices approach problem solving, as shown in their classification of physics problems when asked “which ones are similar?”. Novices tend to sort physics problems according to surface features (e.g., pulleys, springs, ramps, or keywords given in the problem statement), whereas, experts tend to classify problems according to the major physics principles governing the solution of each problem [Chi, Feltovich, & Glaser, 1981]. This points to fundamentally different internal schemas used by novices and experts in representing physics problems [Slotta, Chi, Joram, 1995]. The challenge therefore is to create conditions wherein the differences between expert (teacher) and novice (student) schemas can be made explicit, providing both clues about students’ structuring of knowledge and also opportunities for students to revise their thinking [Reiner, Slotta, Chi & Resnik, 2000].

We conjecture that the movement from novice to expert understanding could be facilitated by providing the students with the expert classification and allowing them to place problems, or phenomena, into these structures and through collaborative negotiation (similar to Vygotsky’s ZPD) attain classification schemes that better mimic those of experts. While individual student schemas may not become the same as those of experts through such collaboration, their combined knowledge around the domain - *as a community* – may come to resemble that of an expert, giving access to individual students for conceptual change [Slotta and Chi, 2006].

2.2.6 Scripting and Orchestration of Learning Activities

In complex, collaborative learning environments activities, it is not enough to simply put the students together and assume that effective interactions or collaborative learning will take place [De Wever et al., 2009; Weinberger et al., 2005]. Rather, we must consider how to support students within the various contexts (e.g., formal and informal environments) and configurations (e.g., individual/small group/whole class interactions) where the learning will occur. Furthermore, individual actions – such as asking a question, answering a question, and the evaluation of answers – will occur in various times and locations, influencing how students understand and process and activity [Lemke, 2000]. Consideration for these factors and their orchestration within the flow of a curriculum is often compared to that of a theatrical script [O’Donnell & Dansereau, 1992]. This scripting can help ensure that the natural granularity of the individual tasks matches the granularity that is most beneficial to student learning. This granularity within the script is often achieved by structuring how and when to constrain interactions, the sequence in which the activities take place, and the specification of individual roles within the larger knowledge community [Dillenbourg & Jermann, 2007].

Scripting can also allow for intentional, “designed moments” of student reflection [O’Donnell & Dansereau, 1992] and for collaboration and communication among their peers [Hakkinen & Makitalo-Siegl, 2007]. By coupling these activities with a technology-enhanced learning environment we can capture the products of these varying interactions and provide them to the teacher, both in real-time and asynchronously, to give them greater insight into students’ understandings of the curriculum and tools with which to orchestrate the activities of the class, on-the-fly [Dillenbourg, Jarvela & Fischer, 2009]. The three iterations in this study investigate how the design of both technology-supported learning environments and the products of students working in these environments can be used by the teacher to better adapt classroom scripts and to orchestrate activities and students in their enactments.

The first study examines how access to students' work on a large projected display helps the teacher understand the state of student knowledge and respond to the needs of the students in real-time. The second iteration provided the teacher with added insight into student knowledge in order to help him adapt the script prior to an enactment of the in-class activity. The third iteration provided an aggregated feed of real-time student group work to the teacher on a tablet computer, and examined how this handheld information affected his orchestration of class activities.

3 Research Questions

The present study addresses the question of how to design curricular activities where students contribute content within a knowledge community and develop a deep understanding of science topics. To guide our development of activities, we incorporate the principles of Knowledge Community and Inquiry [Slotta, 2007; Slotta and Peters, 2008]. Reflection is included as a primary component in supporting students as they make personal sense of the community knowledge, and apply that knowledge to consequential learning tasks. Specific research questions are as follows:

1. What forms of collaborative knowledge construction best supports a knowledge community approach for high school physics?
2. What inquiry activities can engage students with the collective knowledge in such a way that they develop a deep understanding of physics topics?
3. How can we support teachers in using student-contributed materials for the planning and orchestration of curricular activities?

4 Method

4.1 Design Based Research

There is a growing trend in educational research to extend learning beyond the confines of controlled laboratory settings and into the more uncontrolled and natural context of everyday classrooms [Collins, Joseph & Bielaczyc, 2004; Barab & Kirshner, 2001]. In response, scholars have developed an approach known as design-based research, which situates the research directly in the classroom [Collins, 1992; Brown, 1992] and is characterized by continuous cycles of design, enactment, analysis, and redesign [DBRC, 2003]. These iterative cycles can provide researchers with a *locus for refinement* in which designs can be adjusted to account for ineffective elements or delve into unexpected outcomes which can form the basis of new and exciting avenues of research [diSessa & Cobb, 2004]. Such an approach is particularly important for technology-enhanced learning environments, because there are often gaps between how innovations should be used in theory and how they are actually used in the classroom [Wang & Hannafin, 2005; Hoadley, 2002].

4.2 Co-design

As design-based research is deeply situated within authentic classrooms, working directly with teachers on the curriculum's design from the outset is essential. This is especially true with technology integration, as it is further complicated by the teacher's specific constraints and requirements for classroom management. Therefore, the success of any such design depends critically on the teachers' own investment in, and understanding of, the innovation. The most effective way to ensure such buy-in by the teachers is to engage them in a co-design approach [Penuel et al. 2007], where researchers and teachers work closely together in the development of the curriculum and technology elements. This approach provides researchers and the teachers insight into one another's values and perspectives, and ensures that the materials under development are not simply tools for the researcher but also match the curricular goals of the teachers [Peters & Slotta, 2008]. The co-design approach can increase agency, reflections, and ownership by the teacher – a critical aspect to prolonged success and adoption of a research design [Roschelle, Penuel, & Schechtman, 2006].

The present research employed a co-design method, where a physics teacher from an urban high school joined our team at every stage of the process, developing materials and reflecting on their success through all iterations.

4.3 SAIL Smart Space

The new forms of knowledge media and student contributed content described above offer a wealth of opportunity for researchers and curriculum designers who can take advantage of the varying contexts (i.e., within the classroom, at home, or in field activities) and devices (e.g., laptops, smartphones, interactive tabletops, and large format displays). By harnessing these technologies we can provide students with new ways to collaborate across contexts, dynamically generate knowledge, build on peers' ideas, and investigate questions as a knowledge community.

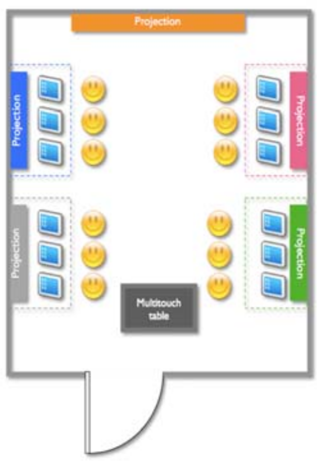

Figure 1: Current Smart Classroom Configuration

Our work recognizes the potential to enable such pedagogical models, and has advanced the notion of a “smart classroom,” that supports research on a wide range of collaborative inquiry and knowledge construction activities. We have developed a flexible open source platform called SAIL Smart Space (S3), which is built upon the SAIL architecture [Slotta & Aleahmad, 2009]. S3 specifies a framework in which devices and displays are configured within a set of core underlying technologies: (1) a portal for student registration and software management; (2) an intelligent agent framework for data mining and tracking of student interactions in real time; (3) a central database that houses the designed curriculums and the products of student interactions; and (4) a visualization layer that controls how materials are presented to students on various devices and displays [Slotta, 2010]. The S3 implementation used in the present research involves four large projected displays spread around the classroom, a fifth, larger, multi-touch display on the front wall, and twenty laptops – all interconnected via high-speed wireless network.

5 Iteration 1 – Tagging and Solving Physics Problems

5.1 Design Goals

Our first implementation of the S3 learning environment was a formative process in which we wanted to investigate some basic approaches to aggregation and representation, as well as our core technology infrastructure. The design focused on an activity that engaged students in the smart classroom around the domain of Physics problem solving. It explored the effectiveness of whole class aggregation for subsequent multiple-choice problem solving by small groups. We analyzed measures of accuracy (of student tagging) as well as the frequency of correctly solving problems. The aggregation of student work was also examined for its effectiveness in aiding teacher orchestration of student activities in response to class conditions.

5.2 Method

Two grade 12 Physics classes (n=32) took part in the intervention. The co-design team consisted of a high school physics teacher, four researchers, and three technology developers. The activity was conducted over two days with two different instructional conditions and sixteen students in each condition.

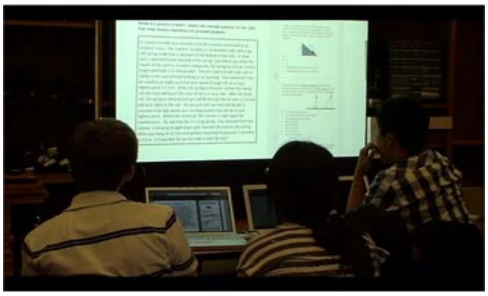

Figure 2: Students gathered around personal laptops in front of a large-format aggregated group display

Within each condition, students were organized into four groups as they worked individually (sitting within their group) to Tag, Answer and provide Rationales (TAR) for a set of sixteen multiple-choice, qualitative physics problems from four distinct themes: 1) Kinetic energy and work; 2) Potential energy & conservation of energy; 3) Force & motion; 4) Circular motion. Once completed, students remained in their groups, where each group received four of the sixteen questions again, along with the aggregated TARs of the whole class. Then, working as a group, asked to form a consensus concerning a "final answer," and to re-TAR the question. After the groups had completed this step, they were presented with four new "long-answer" (quantitative) physics problems. For each long-answer problem, the group was asked to select which of their earlier qualitative problems was most related to the problem, to choose a set of elements and equations that would help set up the problem for solving, and to provide explanations for their choice of formulas. For the second group, we introduced a condition wherein two of the four groups' work was broadcast on the large-format shared displays in the smart classroom, where the other groups used only their laptops for collaboration (similar to the students in day one).

5.3 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 overall curriculum activity; (3) researcher field notes; (4) Follow-up debriefing with the co-design teacher. The combination of field notes and video provided insight into how the smart classroom facilitated curriculum enactment, student collaboration, and teacher orchestration. The follow-up debriefing added to our understanding of the co-design process and the teacher's perceived match of the intervention to their curricular goals. The captured student data was analyzed to determine changes in accuracy of responses between individual and groups, and to determine the accuracy of their element tags.

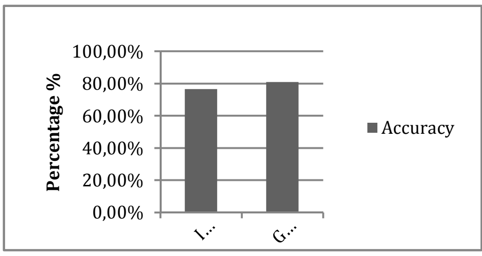

Figure 3: Individual vs. Group Accuracy in tagging physics problems

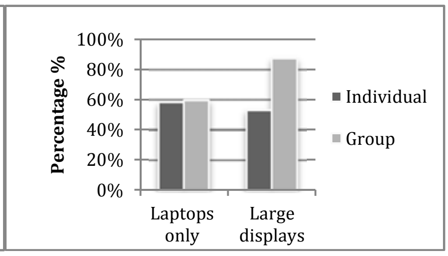

Figure 4: Group versus individual performance on laptops and shared displays

5.4 Findings

The physics element tags (concepts and equations) added by students working in groups across both classes tagged their problems closer to the expert model than as individuals (Figure 3). 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 is concerned with the effect of the condition where half the groups in our second trial were given projected displays in addition to their laptops. Although group versus individual performance was shown by 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 4). One possible explanation is that the large format displays provided the teacher with the ability to see what students were writing in their summary responses, and thereby allow for quick engagement in meaningful interactions. For example, in one episode, the teacher was watching one 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 "in real time" - advising students that, in this case it may be better "not to listen to the wisdom of the crowd."

5.5 Discussion - Iteration 1

The aggregated information appeared to help students in improving their understanding, perhaps through the challenge of reconciling their tags, and hence their framing of the problem under investigation. Moreover, the smart classroom successfully engaged students in working collaboratively with their peers to discuss, debate, and refine their answers. It also appears that the large format display provided some advantage over the small, shared display in facilitating such collaborations. In addition to providing a common visual referent for students within a group, such displays apparently provide the teacher with real-time information about student ideas, enabling adjustments to the pedagogical script.

6 Iteration 2 – Adding Homework to Bridge Learning Contexts

6.1 Design Goals

The second iteration of our curriculum built upon findings from the first, remaining in the domain of Physics. We had concluded that the aggregation of student work was useful for both the students and teacher, however the teacher noted that the activity took a lot of class time to complete. In response, we adapted the curriculum to allow

Figure 5: Teacher Portal

for the first step (the individual TAR of multiple-choice problems) to be completed as an asynchronous homework activity. This allowed the teacher to allocate more time to the synchronous group activity (the "re-TAR" activity) in the smart room. To support the homework process, we added a teacher portal that allowed the teacher to customize the activity (i.e., the number of questions to be served to the students, and the type of questions presented) and provide a report to the teacher concerning the students' homework responses. By viewing this report before coming into class, the teacher would have the opportunity to adjust the upcoming class script based on his perception of the students' understanding. Additionally, the teacher could use the portal during the smart room activity, to examine the groups' work in real-time, which could also inform orchestrations of the in-class activity. For this iteration, we also added a condition where some students completed the group activity in their regular classroom, working in dyads (ie, in order to examine the differences between the collaboration there versus in the smart classroom).

6.2 Method

Two new physics classes were engaged (n=36) with twenty students (n=20) in the first class and sixteen in the second (n=16). The same group of researchers, technologists, and teachers were engage in the co-design of the activity.
The teacher logged into the teacher portal and uploaded questions, five in total, for the students to answer for homework. Students were alerted via e-mail that the homework activity was posted, and completed the individual TAR activity before the start of the next class (two days later). Before the classroom session, the teacher logged into the teacher portal and looked at the aggregated work of the students to develop a sense of what ideas were present amongst the student reflections. During the in-class activity, the students repeated the re-TAR step from the first iteration, (in dyads rather than groups of four) while the teacher was free to use the aggregated visualization to help understand the ideas that were coming from this paired reflection task.

6.3 Data Sources

Data collection for this run was similar to that of the first: 1) All student and dyad tags, answers, and rationales were captured by the system; 2) Researchers collected field notes of the in-class activity; 3) A follow-up debriefing of the activity was conducted with the teacher. For this iteration, no video was recorded of the in-class activity. The in-class field notes provided us with an understanding of how the students were engaging with the curriculum and their peers while in class. The captured student data was examined to reveal changes in the accuracy of responses between students answering individually versus in dyads, as well as in the rationales. Finally, the follow-up debrief with the teacher provided insight into his perceived effectiveness of the added technology scaffolds in meeting their curricular goals.

6.4 Findings

Overall, dyads faired significantly better at solving problems (97% overall accuracy) than individuals working at home (80% overall accuracy), with $t=2.02$, $df=41$, and $p<0.05$. One problem, for example, had marked improvement with 45% of students answering incorrectly at home, but 100% answered correctly in dyads. These results are obviously confounded in that the dyads were solving the same problems that they had seen in homework the night before. But the nuance of problem rationales made it worthwhile to have students re-engage with the same set of problems.

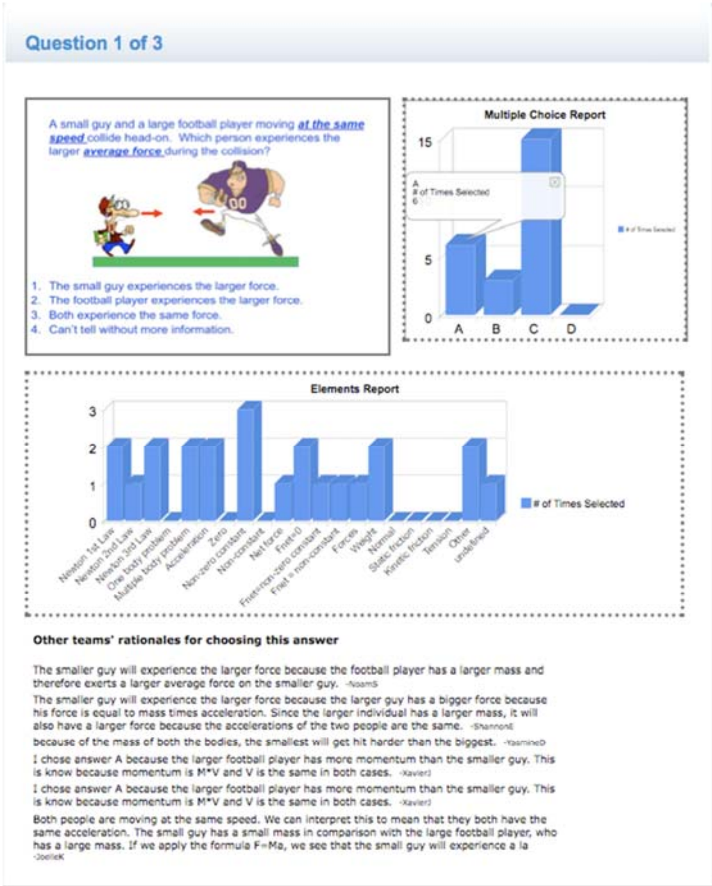

Figure 6: Aggregated student TARs for dyad activity

Throughout the in-class activity, the dyads were observed reading their peers tags and rationales, and engaging in discussion around them, in an attempt to make sense of any differences. Comparing individual rationales versus group rationales showed that in twenty-four cases the dyads' rationales were unique - not identical or nearly identical to any individual answers (with an intercoder agreement of 83%). This indicates that the students did simply regurgitate the ideas of the individual explanations during the re-Tar activity (although it is possible that they simply ignored those ideas, which would be nearly as problematic). 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 real-time reports to be useful in understanding where students were having problems with the content prior to conducting the class. During the first of the two class sessions (which occurred in the smart classroom) despite referring to the report, the teacher decided to let the lesson run without changing the script, preferring to see how the students fared in their dyads. However, seeing the students struggle on one particular problem forced him to intervene (i.e., adapting his "script"). Drawing from this insight, the teacher adapted the flow of the activity more readily on the second day (held in his classroom, with laptops but no projectors) to address issue when they arose reducing potential frustration on the part of the students.

In this iteration, the design of the teacher report required the teacher to refresh his laptop screen to see any updates in students' activities, and this delay made it difficult to know what was happening "in real time." On the second day, this was compounded by the activity not taking place in the smartroom, meaning that the teacher was unable to see the dyads' projector screens at a glance. This made it difficult for the teacher to know the location in the class where assistance was most needed. Although he was able to walk from table-to-table, he did not have targeted information upon which to decide which dyads might need assistance.

In both dyad days (smartroom as well as classroom), students were overheard mentioning that the activity was more engaging than normal problem solving – a statement echoed by the teacher during post-interviews.

6.5 Discussion – Iteration 2

The results of this iteration reinforce our belief that students' access to the aggregation of their peers' work helps them to develop more accurate understandings of physics problems. Results suggest that students did take their peers' rationales into account when constructing their group (dyad) TARs. The teacher acknowledged that access to aggregated student data before running the activity informed his thinking about the upcoming class activities. However, in class, the need to refresh the report screen limited his ability to see the class' work in real time. In response, our future designs will require an automatic updating of any teacher visualization. Finally, moving the collaboration outside of the smart classroom setting and having the students only work on shared laptops further hindered to the teacher's ability to assess student ideas and scaffold class activities in real-time. It appears that "broadcasting" students' group work on a large format display is an important factor in helping the teacher maintain an active sense of what students are thinking.

7 Iteration 3 – Adding Student Expertise Areas, and Teacher Tablet

7.1 Design Goals

Our third iteration attempted to further enhance the teacher's ability to orchestrate the activities of the class as well as to improve our understanding of how students can use the aggregated work of their peers to inform their own reasoning about physics topics. We designed a new teacher report application for use on a handheld tablet computer that used a color-coded matrix (groups-by-problems) to display how each group of students performed on every problem (i.e., green if the group had answered correctly, red if they answered incorrectly). The teacher could press the tablet screen on any of the problem boxes in the matrix to bring up the groups' TAR, which would inform his understanding of how that group had approached that particular problem.

The teacher tablet application also allowed the teacher to show a group their TAR (since once it was submitted, the group did not have easy access to it) in order to engage them in discussion, if the teacher had noticed something interesting or erroneous in their response. We were interested in how this tablet application provided the teacher with new opportunities for understanding the state of student knowledge in real-time and how this might affect his orchestration of activities during class time. Once again, we varied the conditions slightly, between the two classes that took part in this intervention: in both cases, the students completed the TAR homework activity, but only those students from the second group received the aggregated responses of peers. This allowed a comparison of how student groups performed with vs. without access to the aggregated responses of all individuals.

7.2 Method

This iteration once again engaged two grade 12 physics classes (first day n=15, second day n=18) and the same group of researchers, technologists and teacher. Thirty-five questions were uploaded, representing five distinct topic areas. Each student was assigned one topic area, and received five problems (out of seven in that topic area) for homework. During the smart classroom activity, students were placed into groups of five, with one student from each topic area, and given five questions – one from each area – of which no member had seen any during the homework phase. The complex tracking of prior exposure to problems, and selection of unfamiliar items was achieved through the S3 intelligent agent framework, allowing for a design feature that would have been vexing in a traditional approach. For the first group of students, no aggregated information from peer homework was given to student groups; rather, they relied only on group negotiation to solve the problems. During the second day, groups were provided with their all TAR responses for each of their problems, aggregated over both classes. The teacher was also given slightly different conditions: on day one, the teacher had only the large-format (projector) display that was provided for each group of students; on day two, however, the teacher was provided with the tablet that showed the matrix of student responses and allowed queries of groups' TAR responses.

7.3 Data Sources

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 see any changes in the correct responses between students' answering individually compared to in groups without the aggregated work of their peers (Day 1) and in groups with the aggregated work of their peers (Day 2). Finally, the follow-up interview with the teacher gave us insight into the effectiveness of the different tools towards future refinements.

7.4 Findings

Individual and group rationales were examined using a four-point scale developed in conjunction with the teacher to evaluate the depth of student understanding. Two researchers evaluated all student and group responses using the co-developed scale with a 91% agreement between intercoders. Overall the group on Day 2 that received the aggregated responses of their peers significantly outscored both the individuals solving the homework (t=4.13, p<0.01, df=51) and the groups from Day 1 that were not provided aggregated responses (t=4.19, p<0.01, df=50) (See Table 1).

Condition	**Average Score (out of a possible 3)**
Homework	1.32
Day 1 (no access to aggregated data)	1.21
Day 2 (access to all TAR data)	2.0

Table 1: Problem solving accuracy for homework, and group work in 2 conditions.

Similar to the previous iteration, the teacher was observed actively moving throughout the class, interacting with the students where he felt necessary. At several points during the activity, the teacher was able to read rationales being written by the groups and prompted them to refine their thinking and focus on the deeper principles relevant to solving and understanding the problems, rather than just the formulas. The teacher adopted a catch-phrase in such interactions, saying that he wanted to see "words more than numbers." Additionally, the large displays allowed the teacher to look quickly between groups, enhancing his sense of the state of the whole class.

The teacher's interactions with the tablet during this final iteration were surprising. When the teacher first started using the tablet, he was very engaged with the device, clicking on the different group responses to read their answers and to see where the students had made mistakes. However, after a few minutes the teacher abandoned the tablet as he found that it was actually distracting him from the more "real life" flow of activities and interactions within the smart room. He complained even during the session that he felt that he was "missing things" when looking down at the tablet (i.e., rather than up at the screens, or talking with students). He noted that while it was useful to see where the groups had made mistakes on the tablet, this information was only available after they had submitted their answers. Thus, reliance on the tablet was actually inhibiting his ability to intervene at moments that he deemed important. The teacher did praise several elements of the tablet, he found it useful more as a reflective device (similar to the aggregated reports in the second iteration), including the ability to see each groups' tags, answers, and rationales, and the ability to see which groups got which questions wrong. But at present, he did not feel that the tablet was useful for his orchestration of the smart classroom activities.

Once again during this activity, we observed that the configuration of the groups around the large projected displays had a noticeable impact on groups' internal interactions. Overall, the groups were better able to engage all members, as even the students most distal from the controlling laptop could watch the screen and voice their feedback. Most of the groups consisted of five students (a few had 3 or 4, due to absent students or uneven numbers), and it was noted that some students tended to distance themselves from the collaboration. At times, the teacher noticed and intervened, reconnecting those students with their group. The groups 3 or 4 members did not suffer this phenomenon. Hence, we have decided moving forward that the ideal group size is 3 or 4 members, when seated in front of a common display.

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 in the present iteration, as there were no cases where "the wisdom of the crowds" generated a wrong answer.

7.5 Discussion – Iteration 3

The third iteration of our study supported our ideas that the aggregation of students' problem solutions, tags and reflections work can provide an important resource in their sensemaking. We have also made some progress in understanding the role of large-format displays as effective means of aiding the teacher in the orchestration of learning activities during class time. Our experience concerning the use of a handheld device for teachers, reveal the importance of thoughtful design – not only of technology and materials, but also when such an innovation is situated within the flow of activities within the classroom: Its role within the "orchestration script." Our first attempt with such an innovation conflicted with the informational needs of the teacher, in terms of his ability to intervene while the students were *in the act of* solving the problems. This underscores the need to fully understand the "temporality" of when certain information or interactions patterns are relevant within the script. Future designs will further investigate two key elements when aggregating information for teacher and students: 1) What information is relevant in order to aid in collaborative knowledge construction and inquiry; and 2) How do we design the content and delivery (including timing) of information within a smart classroom activity (as well as the broader curriculum) so that it is aligned to teacher needs for orchestration, or the student needs for learning and collaboration?

8 Conclusion

The results of our three iterations suggest several conclusions about learning in smart classrooms. The first, and perhaps most important, is that technology can serve to capture and aggregate student data, representing that information in ways that make it relevant and accessible to students and teachers alike. For students, the aggregated TAR data provided insight into the work of their peers and informed their collaborative problem solving within the smart classroom. The availability of a set of rationales provided by their peers, seems to have provided a real opportunity for sense making and learning within the group discourse.

Our study also shows that the aggregation and representation of the products of student work can be a powerful tool for the teacher, providing insight into the state of knowledge of the class. By making such information available at key points within the curriculum (during planning, enactment, and post-activity phases) we provide teachers with opportunities to adjust their orchestration scripts before and during class. In all three iterations, the teacher regularly referred to these aggregated representations when making decisions about the flow of class activities, and he emphasized, during the post- interview, the value that he placed on these resources.

The S3 technology scaffolded student activities in different contexts, both spatially (at home, in class, in the smart classroom), and organizationally (individual, small group, and whole class). Not only did this provide students with multiple perspectives from which to engage curriculum topics, it also served the teacher well, allowing some activities to be orchestrated in-class, while others were moved outside of the class as homework, with the outcomes then reintroduced as in-class activities.

These studies demonstrate the effectiveness of a smart classroom in supporting the orchestration of collaborative inquiry activities. The physical space, in conjunction with S3 digital agents, was effective in grouping students, displaying information specific to the needs of each of those groups, and providing the teacher with insight into the thinking of those groups, in real-time. The large format-displays proved to be a key technology, allowing students to see their group's work more effectively and teachers to see all the groups' work at a glance. The teacher was also able to use the large displays as a teaching tool – pointing to particular parts of the students' work during discussion and bringing up particular questions on a central display for the whole-class discussion. It will be interesting to think about new patterns of interaction guided by large and small displays, and in re-thinking our designs for a teacher tablet that can be instrumental without detracting from the orchestration.

Moving forward, our ideas and designs for smart classrooms will be scaled beyond a single problem solving and tagging activity, becoming part of a longer, persistent physics curriculum. New questions will arise around how the community's knowledge can be represented, and how the teacher can adapt his lesson plan or immediate orchestration to respond to the emergent ideas that are captured and displayed as a result of collaborative inquiry activities within the student community. Our future research will address the application of such emergent information to help scaffold the community's overall knowledge construction. We will also address questions of student agency in the development of curriculum content – e.g., by having students submit their own questions, or even outside examples such as captured videos and pictures.

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