Supporting the Art of Teaching in a Data-Rich, High-Performance Learning Environment

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INTRODUCTION

Data-driven decision-making (DDDM) has become part of the school accountability and reform lexicon. The term commonly refers to policies and practices involving the use of student achievement and other data (such as attendance, course-taking patterns and grades, and demographic data) to drive school improvement at the school, district, and state levels. In recent years, policymakers and administrators have come to view data-driven decision-making as having significant potential to improve education reform efforts and enhance student learning outcomes. The logic of DDDM is that analysis of data bearing on achievement and other related data will enable schools, districts, and states to identify areas needing improvement and to determine the degree of success or failure of actions taken to improve educational systems at various levels (Elmore & Rothman, 1999, cited in Massell, 2001).

DDDM clearly has an important role to play in school accountability and improvement. As practices of DDDM are increasingly implemented, commercial systems designed to support those practices are proliferating (Light, Honey, Heinze, Brunner, Wexler, 2005; Means, 2005; Palaich, Good, Stout, & Vickery, 2000). However, large-scale assessments, as well as the data management systems that support them, have severe limitations as tools for teachers attempting to inform instruction and instructional decision-making, which can lead to inappropriate use of accountability data (Confrey & Makar, 2005). Large-scale assessments and the data they generate are often not linked to classroom practices and outcomes (Herman & Gribbons, 2001), not aligned with instructional objectives that are pursued in the classroom and embedded in the curriculum (Shepard, 2000; Stiggins, 2001b), do not cover sufficiently the domains tested to give a fair and valid picture of subject-matter learning (Confrey, this volume), and not available to teachers in a time horizon that makes them useful in instructional decision-making (Light et al., 2005). Consequently, data management and reporting systems that use large-scale assessment data are inadequate to help teachers and administrators understand and improve classroom-level instruction, curriculum enactment, and the effects of these on students' learning. Other data are needed, such as classroom-level, curriculum-aligned assessment and performance data whose content is well known to teachers and highly aligned with their instructional goals.

Research has shown that in practice, when performing DDDM with standardized test data, teachers often draw on their own knowledge of students and their classroom work and participation to make sense of or challenge standardized test data (Light et al., 2005). Mason (2002) documented that teachers express a preference for current data relevant to their own students and faculty members, and Thorn (2002) pointed out the mismatch between the kinds of data usually available and the recency and specificity of information teachers need to guide instruction. A growing body of research is documenting that classroom assessments embedded in the curriculum, and thus highly aligned with the instructional goals and curriculum enacted in the classroom, are more appropriate data sources for instructional decision-making (e.g., Shepard, 2000; Stiggins, 2001b).

Confrey (this volume) argues that in the current era of accountability-based reform, state tests have been asked to perform different functions: monitoring schools' progress against a set of state-established benchmarks for student performance, certifying individual students' proficiency, and selecting students for different programs. We agree with Confrey that it is necessary to maintain a clear distinction between data used for administrative and school- and district-accountability purposes and data used for classroom-level instructional decision-making. We argue here that classroom-level instructional decision-making requires classroom-level data suitable for diagnostic, real-time decisions regarding student learning and instruction. Enhancing data use in teachers' instructional decision-making requires technical and social supports for collecting and interpreting data, as well as research on the type of classroom infrastructure that can support teachers' seamless integration of real-time data into their instructional routines.

We do not argue against the need to collect assessment data oriented toward monitoring progress of schools, but we do believe that to support learning, assessment data that are instructionally diagnostic should be collected far more frequently than data collected for accountability purposes. An annual cycle of data collection and use in planning is appropriate for an administrative system and for accountability, with longitudinal data adding value to this process (Herman & Gribbons, 2001). In our view, large-scale assessment data are valuable indicators for administrators, policymakers, and the general public because they provide important feedback information to schools about their performance that can be used in improvement efforts. But these data are of much less use to a teacher diagnosing her students' learning progress and planning appropriate instructional interventions for next week, or to a principal or curriculum coach functioning as instructional leader. For classroom-level instructional decision-making, cycles of data collection and use should be extremely short, from several weeks to several minutes to improve student-learning outcomes (Wiliam, 2007).

The relevance of this distinction is illustrated by considering accountability and decision-making at different levels in other private and public enterprises. For example, hospitals collect, analyze, and report data on patient diagnoses, medical outcomes, mortality rates, and other institutional metrics. Hospital administrators use these data to improve operations, procedures, and protocols, and to identify areas where quality of care needs to be improved. Consumers can use this information to choose hospitals for their own medical needs, and policymakers can use it to inform and monitor budgetary decisions. However, such information is not what physicians rely on to improve diagnosis or to devise therapies for their patients on a day-to-day basis. Similarly, teachers report using a wide range of qualitative, often intuitive, information on a day-to-day basis to diagnose their students' learning and needs. The difference is that teachers must perform such analyses largely without the aid of technologies on which other professional diagnosticians rely.

This chapter reports on research that pursued the question: What would a classroom technology infrastructure look like that would make it *easy* for teachers to capture and analyze complex, nuanced information about students in *real time*, to inform their instructional decision-making, and to individualize and optimize the classroom learning environment *while the learning process is still under way*?

We offer an emerging vision for the future direction of technology innovation to support the use of different sources of classroom-generated data in instructional decision-making. Our work focuses on technology tools to support classroom instruction and explores the largely untapped potential of *real-time data* on teaching and learning *processes* to inform decision-making *during* instruction that, in turn, improves learning outcomes. We subscribe to the position that student evaluation at the classroom level should primarily serve as assessment *for* learning rather than assessment *of* learning (Shepard, 2000; Stiggins, 2001a).

Our initial vision was based in two key premises. First, next-generation classroom technology infrastructure should be designed to support the instructional practices that research evidence strongly demonstrates are effective in improving student learning. Therefore, formative assessment, one of the most effective instructional interventions yet investigated, is a key instructional practice that should be supported by tomorrow's classroom technologies. A meta-analysis of the research on formative assessment by Black and Wiliam (1998) showed that formative assessment interventions achieve effect sizes of 0.40 to 0.70 — effect sizes larger than those seen for any other instructional intervention tested. Formative assessment has been shown to have beneficial effects for student motivation as well. Black and Wiliam (1998) and other researchers have shown that formative assessment and feedback to students about progress and performance is motivating to students and can increase student persistence, sense of self-efficacy, and self-regulated learning (Brookhart, 1997, 2001; Stiggins, 2001b).

Second, design of a next-generation classroom infrastructure should consider the nature of teaching and should take into account the full spectrum of teachers' work flow, work processes, and performance support needs. Specifically, we need to consider that teachers are diagnostic, clinical professionals (Hinds, 2002; Solomon & Morocco, 1999) for whom information on general student learning is part of building up a model of a particular student's learning accomplishments and instructional needs. Teachers perform their work in contexts marked by extremely high levels of cognitive complexity, simultaneity, and time pressure (Berliner, 1994) as we describe below. The technologies teachers generally have available today do not reflect this image of the teacher as a clinical professional because they are not designed to collect, process, and represent classroom-generated data that inform critical socio-cognitive practices of instruction, diagnosis, and reflection.

Our initial vision evolved based on input from several sources. We conducted a study in high school algebra teachers' classrooms that investigated teachers' and students' needs related to learning content, instructional experiences, and work flow, specifically, the processing of student work and provision of feedback to students. We examined these issues from the perspective of improving teaching and learning as well as improving teachers' work flow and workload issues, which are critical issues for teachers and gating factors in the realization of the potential benefits of technology. Our vision of the classroom technology infrastructure was also informed by our analysis of research findings on the use of student response technology (Penuel, Roschelle, & Abrahamson, 2005), as well as our review of currently available educational technologies and trends related to classroom assessment and participation. Current research in the learning sciences on constructivist teaching, assessment, and learning (Bransford, Brown, & Cocking, 2000; Pellegrino, Chudowsky, & Glaser, 2001) also points to the promise of new classroom technologies for providing teachers with appropriate, integrated tools to promote teaching and learning.

Our own design research and our synthesis of others' work are directed toward developing design requirements for a powerful new set of collaborative, interactive, and personalizable technologies for the classroom. The technologies we envision for tomorrow's classrooms will provide performance support for teachers to make complex decisions in real time and will address teachers' work flow needs. These tools will enable teachers to collect data that support instructional decision-making for their current students. Thus, *the learning of the students from whom data are collected can be directly affected*. Our work attempts to improve the quality of student learning data that can be captured in the classroom; automate data capture, analysis, and representation wherever possible; tie data to classroom learning; and eventually eliminate the time lag between construction of data and analysis, and decision-making with those data.

Our vision differs from that of the current advocates of "benchmark testing" and from most other current technological solutions to the problems of gathering and using diagnostic data on student learning. We agree with Shepard (2005), who warns about computer technology being used to administer curriculum-external "benchmark tests" geared toward preparing kids for large-scale assessment that are part of accountability programs. As Shepard (2005) points out, this has the unintended negative consequence of narrowing the enacted curriculum to the limited skills, knowledge, and abilities evaluated by standardized tests. Computerized benchmark testing also represents an impoverished conception of the potential of current technologies, which can support measurement of more complex skills, knowledge, and abilities than traditional assessments (Bennett, 1999; Means, & Haertel, 2002; Quellmalz & Kozma, 2003; Pellegrino, Chudowsky, & Glaser, 2001). But even these technologies should elicit (but too rarely do) careful consideration of the role of the teacher in assessing student learning and making use of data for instructional purposes.

In what follows, we first present some of the bases for our vision of a technology infrastructure for teaching and learning. Then we describe some key themes and findings from our early-phase design research investigating high school algebra teachers' instructional practices and work flow to identify design requirements for a classroom technology infrastructure that improves instruction, diagnosis, work flow, and productivity as well as enhances collaboration and communication among students and between students and the teacher. We also describe the conceptual framework for classroom technology design that emerged from this study. Finally, we discuss implications of this research and examine how application of this conceptual framework could inform the design of a classroom technology infrastructure for high-performance teaching and a learning environment that is data-rich for real-time decision-making and feedback.

EXISTING TECHNOLOGY TOOLS FOR TEACHING AND LEARNING

In this section, we briefly examine some key benefits and limitations of two mature classroom instructional technologies currently in wide use. The first type, classroom response systems (CRSs), is designed for whole-class instruction; the second, intelligent tutoring systems, is designed for individual use by students. Then we briefly examine the use of technology to support summative classroom assessment. This analysis informs our own ideas of design criteria of next-generation classroom technology infrastructure.

Classroom Response Systems

One of the most mature technologies with strong capabilities for collecting information about students' thinking and understandings are classroom response systems — also called clicker systems. This simple technology, several forms of which are available, enables teachers to pose a multiple-choice question and to collect and aggregate responses from all students, with each student inputting her response on her clicker. The aggregated student responses are then displayed publicly, typically as a bar graph, for all students and the teacher to examine and discuss. Classroom response systems are an effective, easy-to-use way for teachers to generate "instant" data about students' thinking. When coupled with knowledge- and cognition-centered pedagogical practices that research demonstrates to be effective (Bransford et al., 2000), this technology can have powerful effects on instruction and learning. The graphical display of student responses provides instant feedback to students about their responses and their peers' thinking. In addition, it offers the teacher a snapshot of students' thinking; the information can feed forward to guide teaching and learning, while eliciting *all* students' active participation and metacognition (Bransford, Brophy, & Williams, 2000; Bransford, Brown, & Cocking, 2000; Roschelle, Penuel, & Abrahamson, 2004; Zurita, Nussbaum, &

Salinas, 2005).

One reason that classroom response technology has been so successful and widely adopted is that it provides the kinds of data about students' thinking that research finds is necessary for effective formative assessment of learning in the classroom (or, as one could describe it, data-driven decision-making *for* learning). The generation and use of these data about student thinking are thoroughly embedded in the instructional process — which is the nature of formative assessment.

Classroom response systems have some important limitations, however, with respect to supporting teachers' instructional decision-making. For example, response systems typically allow for limited student input (responses to multiple-choice questions) and are not integrated with other classroom learning technologies. The utility of data from response systems could be expanded through integration with other tools and databases, allowing the teacher to build up longitudinal databases and sets of questions that are diagnostic of students' understandings. Thus, although we are excited about student response technology and its ability to help teachers understand students' thinking, to motivate students, and to provide feedback, we view CRSs as the tip of the iceberg in terms of what is possible for creating an information-rich classroom in which teachers and students have timely, rich information that can improve processes.

Intelligent Tutoring Systems

Another class of technologies that show promise for providing teachers with diagnostic information about students is intelligent tutoring systems. Advances in cognitive modeling of student learning have allowed technological development that allows teachers and students to access powerful content that is differentiated for students at different levels of mastery and with different learning needs. Intelligent tutoring systems for algebra offer the student instant feedback about mastery of target skills and knowledge, and for the teacher they construct a complex, nuanced model of what students know and can do (Koedinger, Anderson, Hadley, & Mark, 1997; Minstrell & van Zee, 2003).

These systems, too, have limitations that make them unlikely to be complete solutions for supporting an effective diagnostic assessment system. Intelligent tutoring systems rarely take into account teachers' job performance and work flow needs. In addition, at this time neither the reports they generate nor their instructional content can be integrated with any other systems. Thus, teachers cannot use these systems seamlessly to support ongoing instruction. In our classroom research, we found anecdotal evidence that information about students' interaction with the intelligent tutoring system is generally not integrated with the rest of the teachers' instruction and instructional decision-making. Because teachers apparently do not act on information from the intelligent tutoring system reports, students are seldom motivated by the report feedback.

Technology-Supported Classroom Assessments

Technology is increasingly being used to support classroom summative assessments — that is, assessment of student learning for evaluation purposes. Technology can be used in the classroom to generate, analyze, and feed back high-quality student achievement data to support learning and instruction in a timely, usable fashion (Bennett, 1999; Pellegrino, Chudowsky, & Glaser, 2001). When carefully designed to align with the curriculum, standards, and large-scale tests, technology-supported classroom assessment has the potential to generate data that are relevant to the curriculum and usable in guiding classroom instruction *as well as* informing accountability programs (e.g., Wilson & Draney, 2004). However, such assessment systems are very rare. Often technology-based assessments are designed for purposes other than enhancing the learning of the students taking the test, such as the evaluation of a program or for integration into state testing systems that are part of state accountability programs. This, as Shepard (2005) reports, contributes to a narrowing of the curriculum in alignment with the narrow set of topics and skills typically represented on large-scale assessments.

The designs of technology-based classroom assessment tools are often limited, from both an instructional and a work-performance perspective. From an instructional perspective, teachers may not be sufficiently familiar with the content of the assessments to interpret students' results quickly and accurately. Each assessment item should be aligned clearly to specific knowledge, skills, and abilities (KSAs) targeted in the curriculum; if the KSAs tested by the item or set of items are not well known to the teacher, her use of the data will be limited. For example, one type of well-designed multiple or constructed-response item diagnoses common misconceptions. For this reason, formative and summative assessments that are embedded in the curriculum are likely to yield information that is more meaningful to teachers and students and therefore more readily integrated into the teaching-learning process.

From a work flow perspective, to the extent that classroom assessments are ad hoc, one-off tools, they are of limited value with respect to improving workflow and providing ongoing support for classroom learning processes. One example of this type of technology-based assessment of complex problem-solving presented in Pellegrino et al. (2001) is MashpeeQuest, an online performance task in which students are asked to develop an argument using web-based historical documents. The technology supports the task in two ways: (1) the information literacy skills that the task is designed to assess are embedded within the technology, allowing evaluators to study skills in context; and (2) the actions students take can be captured through the technology and analyzed as problem-solving pathways.

This type of assessment is particularly useful in program evaluation, in that it can be aligned to the instructional goals of particular curricular programs. At the same time, the specificity of the assessment limits its wide applicability for instructional decision-making in the classroom. MashpeeQuest was designed as a summative performance task, not as an ongoing assessment of students' reasoning and problem-solving skills. More critically, this assessment tool does not articulate with any other learning or teaching tools in the classroom. For example, data on student performance generated from the web-based assessments were not inter-operable with analysis tools the teacher could use to review the result. In short, this technology-based assessment was another disconnected "silo" technology in the classroom.

NEXT GENERATION NETWORK TECHNOLOGIES FOR CLASSROOM INSTRUCTION

Each technology briefly discussed above (and there are many others) constitutes a promising development for increasing the feasibility of individualizing instruction for students, increasing the amount and quality of cognitive information that teachers and students have about student learning, and improving student learning. However, from the teachers' and students' perspectives, each technology exists largely as a silo. Each must be mastered, adopted, and integrated into classroom practices through distinct processes of training, planning, integration, etc., and data and resources from one cannot be ported to another. Furthermore, adoption of each new technology has a cost, both financially and in terms of time and effort, to learn, integrate, master, and adapt one's practices to optimize the tool's potential to improve learning and teaching. Thus, the proliferation of technologies has the unintended consequence of further taking teachers' time and attention away from core instructional tasks. The benefits of each type of technology just described could be multiplied if they were integrated into a single classroom network platform.

Advances in network technology and computation offer a way forward that can reduce the financial, temporal, and administrative overhead of technology adoption while dramatically improving teachers' work flow, reducing workload by eliminating routine tasks, and, most important, improving teaching and learning. New affordances of wireless networking as well as portability and mobility in computing devices constitute an opportunity for educational researchers to demonstrate that high-quality assessment data can be gathered in classrooms and made available to teachers, students, and parents to inform changes in instruction as learning occurs, not after the fact. The next generation of technologies can potentially transform the quality and timeliness of classroom assessment *for* learning, resulting in substantial increases in student achievement.

DESIGNING TECHNOLOGY FOR TEACHERS AS HIGH-PERFORMANCE PROFESSIONALS

As instructional and classroom assessment technologies continue their advance into more and more classrooms, we must ask: How well do these advances reflect and support what we know about accomplished teaching? Put another way, if all teachers had all of these technologies available on their desktop (as predicted by Palaich et al., 2000), would we see a real jump in the quality and productivity of teaching? The technologies described above assume different pedagogical strategies, classroom management techniques, and activity structures that place different, often competing cognitive, temporal, and social demands on teachers and their students. New design frameworks are needed to move from a toolkit consisting of often incompatible tools that make competing demands on teachers' time and technology integration strategies to an integrated infrastructure that supports high-performing classroom systems.

Our approach to the data-rich classroom in which students and teachers have access to sophisticated content and services is not aimed at eliminating the need for teachers' professional judgment, as some fear, but, to the contrary, at providing teachers with the kind of technology tools and computing infrastructure available to other high-performance professionals, such as physicians and air-traffic controllers. This approach has the potential to help teachers optimize the learning processes that students engage in throughout the day and the year in ways that contribute to maximizing learning *outcomes*.

To unlock the potential of technology to support teachers' ability to engineer a powerful classroom learning environment, technologies that today are available largely as silos must be integrated into a coherent infrastructure that (1) supports all aspects of the teacher's performance of her job and (2) provides her and her students with powerful learning tools. Indeed, these two goals are intertwined — one of the teacher's key goals is to create a powerful environment that optimizes student learning, individually as well as collectively. To inform our analysis of the ways that classroom infrastructure designs can best support rather than hamper excellent teaching, we turned to the teaching literature to understand what expert teachers know about their students' learning states, how they know it, and what they do in the day-to-day context of teaching to help their students learn.

Teaching involves agility with a domain content, keeping students engaged, quickly assessing what students know and can do, diagnosing student misconceptions and instructional needs, and selecting alternative instructional strategies on the fly. This work is cognitively demanding. Teachers make decisions at a rapid rate, operating in conditions of high levels of simultaneity, with frequent interruptions. The teacher is responsible for assuring that *all* students are *productively* engaged; determining when students' engagement with content, peers, and tools is not having the desired results; and deciding what to do to maintain or correct the course of action. Teaching is increasingly viewed as akin to the clinical professions, requiring acute judgment, continuous problem-solving, progressive learning from unique cases, and the integration of many domains of knowledge and skill (Ball & Bass, 2000; Berliner, 1986, 1994; Hinds, 2002; Solomon & Morocco, 1999). However, unlike other professionals who perform highly complex work that is highly consequential for society, such as physicians or air traffic controllers, teachers do not have the data-rich, performance support, and information-feedback work environment that virtually all other high-performance professionals and many service professionals have at their disposal.

BUILDING A BETTER UNDERSTANDING OF TEACHERS' TECHNOLOGY NEEDS: A REQUIREMENTS ANALYSIS OF TEACHING ALGEBRA

Guided by an understanding of the state of the art in classroom assessment technology and a view of teachers' work as clinical, time pressured, and cognitively intensive, we began our empirical research aimed at developing design requirements for a classroom technology infrastructure that addresses teachers' job performance needs and creates a data-rich classroom in which easy-to-use information is readily available to guide instruction and improve and individualize learning while enhancing opportunities for collaboration and communication. Such a learning environment would support *high-performance* teaching, as well as enhancing students' active, metacognitive participation in learning.

Our initial focus was to describe and understand teachers' practices and then to begin to identify latent and manifest needs that could be addressed through technology. Our immediate goal was not actually to develop and test such a classroom technology — that undertaking is a long, multifaceted process — but rather to develop an analytical framework and design principles to inform later development and testing of this possibility. The study we describe here thus represents early-phase design research with the modest goal of developing a framework to inform the design of an integrated solution that makes rich, complex, and multiple forms of data readily accessible to students and teachers.

The study focused on high school algebra teachers and classrooms. We selected algebra as a content area in part because this subject is a chokepoint in the academic pipeline for mathematics and science education, so that improvements to teaching and learning in this area have the potential to increase the flow through the math and science pipeline, and in part because relatively mature educational technologies (e.g., Cognitive Tutor) are available for this subject area.

The study was conducted over seven months by a multidisciplinary team of researchers with backgrounds in mathematics teaching, student assessment, social cognition, and technology, and included extensive involvement of eight high school algebra teachers.

Methodology, Design, and Data Sources

Our study used a multiple-case comparative design with methods drawn from research technology design research as well as empirical methods from cognitive ethnography (e.g., Hutchins, 1995, 2000) and rapid ethnography (Holtzblatt & Beyer, 1996; Holtzblatt & Jones, 1992), using an adaptation of grounded theory methodological approach to theory elaboration (Glaser & Strauss, 1967; Strauss & Corbin, 1990). Cognitive ethnography emphasizes qualitative data collection and analysis to describe situated practice with a focus on the tool-mediated nature of sociocognitive processes in work practices. Similarly, rapid ethnography entails qualitative methods to document work practices and activity structures, and relies on researchers and participants who represent differing perspectives on or within the practice or activity system under analysis. The term “rapid” applied to this approach reflects the relatively rapid cycles of data collection, analysis, design, and testing typically involved in technology design and development.

Grounded theory methodology (Glaser & Strauss, 1967; Strauss & Corbin, 1990) was a suitable approach because our design goals necessarily need to be deeply rooted in the phenomenon under investigation. Grounded theory is a data-rich, inductive, and comparative approach to theory elaboration that makes it appropriate for a case study design. Researchers begin data collection with a set of categories, working assumptions, and research questions that guide data collection, and, through a cyclical process of data collection and analysis, revise the research questions with increasingly greater focus. When used with a comparative case study, hypotheses are tested through abduction (Peirce, 1955; Shank, 1987), whereby the researcher tests the generalizability of the theoretical description of a phenomenon from case to case (as opposed to statistical-inference-oriented research, in which the researcher aims to generalize a measure of some variable from a sample to a population). This grounded theory process was used to develop an analytical framework for classroom technology infrastructure design rooted in the needs and behavior of teachers and students, in the context of a multiple, comparative case study design, with flexible use of design and data collection methods (Yin, 2003). The research design is represented in Figure 1.

The grounded theory process cycled through three phases of data collection and analysis, each phase successively honing the research questions, foci of the data collection efforts, and analyses of the data: (1) exploratory research phase, (2) focused inquiry phase, and (3) validation phase. All six researchers on the research team were involved in all phases of the research activity. Data collection instruments, activities, and analyses in the first and second phases were oriented to the following:

- Documentation of the teacher's in-class and out-of-class work processes related to a list of critical instructional tasks, drawn from Shulman (1987) with some additions of our own:
    - Evaluating students in class and out of class
    - Creating assignments and assessments
    - Tracking student assignments
    - Interpreting and responding to students' ideas
    - Tracking students' work productivity
    - Tracking students' work performance

- Teachers' strategies for knowing what students know and providing feedback. Knowing what students know and can do and where students need further guidance and practice — and how best to provide them — is perhaps the core task of teaching. We pulled this task out from Shulman's (1987) list as worthy of particular focus.
- Work flow (activity flow), productivity, and efficiency within the classroom: Work flow was primarily tied to artifacts, including student work assignments, communications about student assignments and subject matter, students' work, teachers' evaluation of students' work; and information (data) collected or available about assignments and students' work.
    - The daily routine of the algebra classroom ─ specifically, the sequence of events around the lesson.
    - Students' classroom participation, communication, and activity.
    - The nature of algebra content in the enacted curriculum (whether the focus of activity and discourse was primarily conceptual, primarily procedural, or some of both).

After each round of data collection (working with two teachers), researchers analyzed and synthesized the qualitative data (field notes, interview notes, and transcripts) individually or in pairs. Next, all researchers met together to compare and hone analyses, and refine the research questions. This process, typical of grounded theory, was followed through each phase of the study. During each phase, the following data collection methods were used.

- *Exploratory Research Phase Methods*
    - Unstructured classroom observation (two per participant)
    - Job-shadowing observation (two per participant)
    - Debriefing interviews (on classroom observation and job shadowing) (one per participant)
    - Participant interview

- *Focused Inquiry Phase Methods*
  - Semi-structured classroom observation
  - Structured job-shadowing observation
  - Cognitive interviews about tasks (using observation notes)
  - Teacher logs
- *Validation Phase Activities*
  - Analytical framework for design
  - Creation of animated slides of a networked classroom design
  - Focus group interviews to review design

For data collection, the six researchers were assigned in pairs to an expert and a novice teacher.

Insert Figure 1 about here.

Participants

The participants were eight high school algebra teachers in the San Francisco Bay Area who received stipends of $1,000 for their involvement. Their courses differed in level, but all were below Algebra II. We deliberately selected teachers from schools with varying proportions of students with low-socioeconomic status. Two teachers taught at one of the poorest districts in the state, and two taught at one of the highest-performing high schools in the state. Four teachers were novices (defined as three or fewer years as a classroom teacher), and four were experienced (defined as six or more years of teaching). The technology they used was generally similar, consisting primarily of whiteboards or chalkboards and overhead projectors. None used intelligent tutoring systems or other computer-based instruction. About half the teachers had students work in small groups regularly or daily and half did not. About half of the teachers made use of manipulatives (such as tiles) or other types of representations.

Algebra Classroom Routines

Algebra classroom routines are the activity structures that must be integrated into any successful performance-supporting technology, or else replaced or transformed if new technologies introduce new goals for learning. We observed substantial similarity in routines across the eight teachers, with some important variations in key tasks and orientation to goals. .

Typically, the algebra teacher begins class by giving students a small set of warm-up problems (on the whiteboard or chalkboard or on the overhead projector) to work through. While students are working (or expected to be working) on the warm-up problems, the teacher may take attendance or may move from desk to desk to check students' homework from the prior evening. It sometimes happens that if students are not held accountable by the teacher for showing her or him completed work on the warm-up problems, they may use this time to complete their homework, either by working problems or, as researchers sometimes observed, by copying another student's homework. The purpose may be "compliance" (to see whether the student did the homework) or, less frequently, "performance" (whether the student understands the material and does the problems correctly); the process and pacing of this homework check typically reflect the differing goals. For example, if the goal is to check compliance, the teacher may mark the homework with a rubber stamp. (All stamped homework is turned in at the end of the week or the unit for course credit.) If the goal is to check performance, the teacher may save time by checking only the two problems she deems most difficult. If a performance check shows much student misunderstanding, she may review some procedures or concepts at the board. One teacher described this process as a "waste of time" because many students in her classes manage to copy homework answers either from their friends (before or during class) or from the answers on the board (instead of using them to self-assess their homework).

The teacher usually spends five to fifteen minutes on the warm-up problems and homework review. Sometimes the warm-up problems relate to the next homework assignment; sometimes the teacher selects problems that review a topic germane to the day's new materials. During the warm-up problems, some teachers ask students to come up to the whiteboard to show their solutions, while other teachers put up the answers on the board and let students self-assess their work.

Next, the teacher introduces some new material, usually through lecture and demonstration on the board (or overhead projector), through guided problem-solving — a process more interactive than lecture-demo — or through a simple demonstration of problem-solving procedures. Alternatively, rather than lead the class, the teacher may introduce a new set of problems for students to work out in small groups and provide assistance as she or the groups judge help is required. The goal of this approach is to allow students to discover how the new material is different and to devise solutions while helping and motivating each other.

Typically, the remainder of class time is spent mostly on students working through problems on the new materials, so they can ask questions of peers or the teacher. Sometimes the next day's homework assignment is to complete the new problem set, which motivates students to use class time to complete the work, rather than talking with friends or addressing other coursework. If the homework assignment differs from the problem set, the teacher announces the assignment before the end of class and allows students to use the remainder of class time to work on the homework.

When not checking homework or recording attendance, teachers typically walk around to monitor student activity and informally evaluate students' understanding of the target procedure or concept. If students are on track, teachers may offer praise, encouraging them to continue their good work. If students are making mistakes, teachers may scaffold their performance or point out errors. Often, if a teacher sees more than one student exhibit the same error, he asks for everyone's attention at the front of the room and instructs all the students at once on the point. In a few cases, however, teachers remain at their desk and complete their own work (e.g., grading papers or doing work for a class they were themselves taking) and interact with students only when one requests their attention.

Class concludes in a variety of ways. Sometimes students simply leave when the bell rings. Sometimes the teacher ends class with a brief wrap-up, summarizing a lesson, giving an overview of the evening's homework, or collecting student work done in class. Sometimes, time simply runs out and the wrap-up does not take place.

Knowing What Students Know

One of a teacher's essential tasks is to determine what students know and what they are struggling with. Without this knowledge they cannot determine what instructional guidance or experiences will help students, nor can they evaluate students. We observed teachers using both formal and informal processes to evaluate what students know and can do, during and after class. For example, teachers often perform a quick, informal check of whether most students have understood the prior day's lesson to decide whether to move on to new material or engage further with the current content. Quick checks include reviewing homework at the beginning of class or asking "Any questions?" at the end of an explanation or lecture. Sometimes, teachers need to examine an individual student's work closely to determine the source of an error or nature of a misunderstanding. Formal evaluations to ascertain what students know are typically quizzes or tests that take between 10 minutes and the entire class period. Besides helping teachers uncover what students know, formal evaluations are a mechanism to encourage or pressure students to master the target material.

We examined teachers' efforts to learn what students know not from the perspective of assessment theory, pedagogy, or accuracy of assessment information or inferences, but from the perspective of *work flow, workload, time effectiveness,* and *efficiency*. (By *efficiency*, we mean the teacher's subjective perception of the value of information collected given the time *and* effort required from students and the teacher for various strategies.

Best Strategies for Determining What Students Know

In our first round of interviews, we asked teachers to describe their strategies for formal and informal assessment and to specify which delivered the most usable information about what students know and can do. We did not ask explicitly about the most time-effective strategies, assuming that whatever teachers reported actually using would be time-effective, given the overwhelming demands on their time. The teachers were evenly divided between considering formal assessments (e.g., a quiz) vs. informal classroom observation and review of student work as more informative. Teachers who preferred quizzes indicated that the diagnosis was more systematic and the reliability of information was greater because students exerted more effort and the information was deeper. These teachers described quizzes as follows:

- I think the most helpful is the quizzes, simply because I can detect what they actually are understanding, the way they're understanding it, so that I can prepare them better for the big test.
- Unfortunately, it's the quizzes and the tests. I mean that's where they put in their most effort just because they know it's going to be graded; it's going to be recorded. It's a lot more formal to them so that's a better assessment for me to see what do you really know. The unfortunate part is it happens once every week or once every two weeks.
- [Q: What about when you circulate and then see how they're doing?] A: Well, that works great, but I feel like I can only — I can never get around to every kid, ever. There's never enough time.
- We like a five -minute quiz [at the beginning of class] just to check in on a skill to see where everybody is.

Teachers who preferred informal assessment during class time described a variety of informal evaluation strategies as useful:

- In most cases, the energy of the class is what can tell me. If in most cases, if they're all getting it, then it's very energetic. . . . Otherwise, the quieter the class is, the more difficult it is for me to read it.
- It's typically by the class discussion that happens. . . . And then I think that's substantiated or backed up by their quizzes and their tests, and the fact that a lot of them are actually attempting their homework.
- And I gain the most about learning from him [a student the teacher doesn't know well], I'd say, by what he does in class.
- It's typically by the class discussion that happens.

- Well, I'm assessing them constantly in class by walking around.

These teachers said that by observing students work, they gleaned important information about student learning and got a "sense" of their level of engagement with instructional materials.

Tradeoffs in Strategies to Know What Students Know

One key finding about teachers' efforts to know what students know is that teachers view their strategies as a series of tradeoffs between time and effort required to gain the information and quality and quantity of information. Nearly every teacher talked about the *tradeoffs* necessary between formal and informal assessment. They generally seek and stick to strategies that are optimally *efficient* — that is, that produce the highest quality of information (depth plus breadth) possible within their tightly circumscribed time limits and heavy workloads.

This finding is consistent with Black and Wiliam's (1998) study: Teachers make decisions regarding formative assessment within a tension-filled problem space in which their internal values about instruction and assessment are in tension with external pressures that affect the way they work. That study, however, explores teachers' beliefs about assessment. Our study explores teachers' reports about their actual assessment practices and the work conditions that constrain their selection and implementation of assessment practices and strategies. Another study, by McMillan and Nash (2000), investigates teachers' decision-making about assessment, but surprisingly, the results , reported in McMillan (2003), make no mention of considerations of workload. In contrast, in our study, teachers' workload and the time and effort required to assess students are primary considerations for teachers. When we asked five teachers (four highly experienced, one novice) in our study to rate the level of challenge or "problematicalness" of 20 aspects or tasks of teaching — on a scale from 1 to 5, with 5 representing greatest degree of challenge — the three topics receiving the highest mean ratings (indicating greatest challenge) all had to do with time: time required for preparing lessons, time required for reviewing student work, and time required for individualizing instruction. The next-highest-rated “problem” was the limited opportunities for sustained examination of one’s own practice in order to improve. Time required for performing formative and summative assessment ranked sixth.

We found that the teachers used a variety of strategies to balance quality and sufficiency of information with time requirements to gain the information. Teachers varied in their assessment of these necessary tradeoffs to learn what students know. Some felt their information was only adequate, lacking richness or thoroughness for specific students or the class as a whole. Others felt their knowledge of individual students’ skills, abilities, and understandings were accurate and rich.

The theme of tradeoffs between quality and richness of information and time required to obtain the information was recurrent in connection to both formal and informal assessment strategies.

Formal Assessment

Teachers in our study cited formal assessment as one of the most difficult aspects of teaching, along with classroom management and engaging all students in learning. Their description of the challenges of formal assessment emphasized the problem of time requirements rather than of technique or professional skill or knowledge—the issues on which most research on classroom assessment focuses. We asked teachers to describe their processes when preparing, administering, scoring, and recording results from a formal assessment. The basic tasks in giving students a quiz are the following:

- Preparing the quiz or test, including selecting or creating the content of the items as well as creating and copying quiz papers
- Administering the quiz or test during class time
- Scoring the individual quiz or test
- Entering scores into the grade book
- Returning papers to students during class

Each task, other than class administration of the quiz, requires a significant amount of the teacher’s out-of-class time. The actual test administration takes time away from instruction, so if the test feedback does not benefit learning, the test is not time-effective with respect to instruction (Stiggins, 2001b).

During interviews and focus groups, teachers made the following representative statements regarding grading and formal evaluation:

- Biggest pain? Grading, number one. So I'm writing over a hundred comments and it probably takes me two hours a class. That's just a lot of time; I've got five classes. . . .
- The grading of papers is always time-consuming and hard to deal with, but a necessary part of assessing students.
- Making up new tests and quizzes for every unit that are different from last year's test and quizzes. That is extremely time-consuming. Getting answers, making review sheets.

Teachers in our study used a variety of strategies to reduce the time and effort needed for each step of formal assessment. For example, a teacher may sometimes have students score each other's quizzes, or he might have students write test questions and submit them for credit, then use their questions on the test. Sometimes teachers minimized the extent to which they provided written feedback on student papers to shorten the time required for marking.

This is a critical tradeoff in formal assessment: detail, quality, and quantity of feedback information provided to students about performance on the assessment and the time required to provide this detailed information. This tradeoff emerged in our findings as a persistent issue. There are two sides this issue: the amount and quality of information the teacher is able to provide back to the student, and the amount and quality of feedback information the teacher herself is able to gain from grading or analysis of student work and the time required to do so.

Teachers expressed concern that the less information provided to students about their work, the less the assessment will benefit learning. Nearly every teacher in our study expressed the desire to make formal assessments valuable in the learning process, and nearly all lamented the time pressures that prevented them from providing more individualized information to students. For example, some teachers use peer grading to reduce the time required for marking student papers and do not collect the papers. This approach, however, gives the teacher no information about student performance. This feedback is strictly for the students' benefit, although having students indicate (e.g., through raising hands) their score could give a teacher some minimal feedback.

Informal Assessment

Teachers in our study discussed informal assessment strategies and goals both in terms of understanding what students know and in terms of monitoring students' level of participation. However, the latter was typically related to the former. Like the teacher who said she got a feel for the students' level of understanding based on the "energy level" of the classroom, some teachers felt that students' level of engagement with the activity was indicative of their level of understanding of the assignment. We did not assess the accuracy of teachers' assessment of student understanding on this basis. However, there are findings that teachers tend to rely overly on activity information and underuse cognitive information in judging classroom learning through informal strategies (Duschl & Gitomer, 1997). On the other hand, as described above, it may be that the sheer cognitive load of orchestrating classroom activity and students' social interactions plays a role in limiting teachers' ability to discern more subtle and complex forms of cognitive information from students' classroom activity.

Informal evaluation during classroom activities was described by teachers primarily as monitoring completion of the work and its accuracy. The theme of tradeoffs between time and quality of information (for students and teacher) was prevalent in teachers' discussions of this topic. When asked during interviews to describe the processes for formative assessment, teachers said:

- Go around the room checking …
- See who's participating and who is not participating.
- It's one of my top priorities is to be giving constant informal feedback. So you just can't do too much of it, and having the energy to keep it going.
- [I try] to look at their work, but you don't really have much time with any one kid or any one group because there is just so many of them. So many kids, so little time.
- I monitor as I walk around. But, of course, I'd love to one day be able to collect them all, check them all for accuracy, as well as effort, and just to see what their mistakes are, and be able to turn them back the next day.

Assignment and review of homework were also described as important but highly problematic as an informal assessment strategy. In general, homework was viewed as necessary to give students practice with concepts and skills, but inefficient and ineffective as an assessment tool, primarily because many students did not complete it; because with students copying each other's work it was an unreliable indicator of a their understanding; and because it is time-consuming to process. On the whole, the teachers perceived homework as difficult to grade and difficult to manage; further, they had problems motivating students to do it.

As with formal assessment, the critical tradeoff in informal assessment is the amount and quality of feedback information provided to students and the time required for the teacher to produce that information. Most teachers in our study felt that it was extremely important to provide as much feedback as possible to students, and the limits in their capacity to do so (in terms of time, resources, and tools) were a source of frustration to them. As one teacher said in an interview, "The biggest, absolute biggest pain in the neck is the daily problem sets. How I can assess them? Now, if I was a very thorough teacher, I'd probably spend 20 hours a day going through every individual problem set. I would like to really see all their work and be able to intervene at a much deeper level, but it's just, time won't allow it."

AN ANALYTICAL FRAMEWORK TO GUIDE DESIGN OF CLASSROOM TECHNOLOGY INFRASTRUCTURE

Our research on teaching and learning activities, communication, and work flow in algebra classrooms moved our thinking about classroom activity and classroom technology infrastructure in the direction of systems theory (e.g, Checkland, 1981). Classrooms are learning *systems*, and systems have emergent properties that are not reducible to individual elements within them. A systems framework of the classroom will help designers of educational technologies and instructional interventions move beyond the one-off, silo solution, toward an integrated solution that builds capacity for teachers and learners.

Through the design requirements study described in this chapter, we came to believe that addressing the classroom as isolated lines of activity by 30 students and their teacher cannot unlock the potential of technology to enhance classroom learning. In particular, our findings regarding the challenges teachers face in processing (grading or marking) student work and providing feedback in a time frame and form that can truly enhance students' learning points to the necessity of a classroom technology infrastructure that augments teachers' capacity to construct and provide feedback by decreasing the time needed to process student work. In addition, our findings regarding the constraints that limit scrutiny of students' activity, work artifacts, and needs highlighted for us the need for increased channels of communication and flow of information, as well as for greater amounts of information for teachers and students about classroom cognitive and social processes in readily usable form. Thus, the bandwidth for interaction and collaborative activity should be enhanced (Hamilton, 2004) so that students and teachers have increased channels for communication and providing information and feedback to each other.

Teachers' work and the teaching and learning activities in the classroom need to be viewed in an integrated, holistic way. Classroom routines such as communication, individual and collaborative interaction with learning materials, and teacher regulation of student learning functions occur as simultaneous layered processes across all students at once. Similarly, the work of teaching involves engaging 30 students simultaneously and extends beyond classroom time to include processing student work, analyzing student data, and so forth. Design of infrastructure to support a powerful classroom learning environment needs to take into account both the in-class and outside-of-class dimensions of teachers' work.

Our systems perspective on the design of classroom educational technologies sees the power of technology as extending well beyond the current individual discrete-tool-based approach or even the metaphor of the "smart desktop" (Palaich et al., 2000). We posit instead a networked classroom technology infrastructure for data-rich teaching and learning with digital content, in which computer-supported classroom assessment is one of many services offered through a platform. Like Palaich and his colleagues, we see the teacher as a knowledge worker who desperately needs integration of the technology tools available to her. But beyond that, we envision something closer to a classroom platform for services (intelligent systems, digital resources, online activities, community tools, and so forth).

Through our iterative analysis of the core activities of teaching and learning in the classroom and the attendant issues of time, productivity, work flow, and engagement, we distilled a set of four analytical constructs, which we set in relation to each other within a framework that emphasizes their interrelatedness. Our framework posits a holistic view of the classroom as a highly integrated system of actors, tools, and content engaged in individual and social learning activities over time. This perspective accords with Hutchins's (2000) view that a cognitive system comprises all the actors within a setting, their interactions with each other, and the technical and cultural tools they interact with, not just the "head" of a single user interacting with a system. The analytical framework we developed is intended to inform design of a classroom infrastructure (network and tools). We believe it is generalizable to other activity settings in which actors use tools and collaborate in task activities.

The framework, shown in Figure 2, views the classroom as a space in which four dimensions, or layers, can be described. The goal of classroom technology design, from this perspective, is not to *maximize* the density (number) of events in each of these layers but to enable students and teachers to *optimize* them for particular pedagogical or curricular objectives in a continuously changing learning context. Each element of this framework is described in turn.

Insert Figure 2 about here.

Cognition. Student learning is characterized in the literature as a function of several cognitive, social, and affective factors, including student engagement, participation, time on task, regulation, feedback, and students' accountability for completion and quality of classwork and homework. We use the term *cognitive density* to describe the aggregate level of students' engagement with learning materials and thinking, their progress in learning, their communication, and their use of time — that is, productive activity in the classroom at a given time. Increasing cognitive density is a general approach to improving learning and is independent of any specific pedagogical intervention. Cognitive density is a second-order effect of the interaction among more basic and measurable constructs: communicative, content, and temporal densities of the learning environment.

As our study showed, engagement, participation, time on task, regulation, feedback, and student accountability participation or products produced during class are interdependent and often not under the direct control of, or even known by, even highly accomplished teachers. Our framework suggests that giving the teacher the ability to fine–tune, fluidly and continuously, the interaction of time, communication, and content will help teachers achieve and maintain optimal cognitive density across classroom routines.

Communication. Communication in the classroom can occur in speech, writing, or gesture and can occur digitally or unmediated by technology. Messages can be sent in parallel or serially — one to one, one to many, many to one, many to many. Hamilton (2004) has described how technology can be used to increase the interaction bandwidth of a classroom. Imagine a networked classroom in which students have tablet PCs on which to accomplish their work. Interactional bandwidth is increased through screen-sharing capabilities and instant messaging, channels of communication that supplement the oral modality that typically predominates in the classroom. Furthermore, a message buffer, for example, of students' queries to the teacher, can allow the teacher to review multiple written messages simultaneously; then, seeing many students with the same question, she can simultaneously send out a single appropriate reply to each student with the same question. Alternatively, students could post questions to a central location, and students who know the answers could reply. Such configurations can dramatically expand the *communicative density* of the classroom. We speculate that when more communication is occurring within the same time frame and, functionally, students are asking more questions and receiving more help, students will experience less "downtime" and greater time on task, which in turn increases the cognitive density of the classroom. Of course, we do not advocate uncontrolled and unmonitored “free-for-all” communication in the classroom, but rather the ability to tune the communication patterns and density to optimally support the desired activity (whether that be small group, whole class, or individual work).

Content. Content includes ready-made resources as well as artifacts generated by students or teacher. It also includes students’ solutions and other work produced by students and teacher. Typically, students’ interaction with content is heavily mediated by the teacher (Ball & Cohen, 1999). Even within the paradigm of “reformed instruction,” in which the teacher is encouraged to act more as guide than as transmitter of knowledge, students are fairly restricted in their access to instructional resources that could enhance differentiation of learning and learner-centeredness of the learning environment. While Internet access in the classroom in theory astronomically increases the availability of resources to students, it is almost impossible in practice for the student or teacher to find instructionally relevant resources that are optimal to promote student learning at a given moment in a lesson or a unit. Other constraints also limit students’ and teachers’ access to content and information. For example, as discussed above, it typically takes days or even weeks for the teacher to process students’ completed assignments (score it, make comments, record results, and return it). Thus, access to an instructionally valuable (to teachers and students) type of content—feedback—is severely limited.

If students had access to digital curriculum content (which could also be printed out) and intelligent services (e.g., instructional feedback or assessments) through a platform rather than as handouts or textbook pages, learning could be more effectively self-regulated and self-directed. Students could complete and submit work and gain feedback immediately. This information could be fed into a system that builds a complex model of the students’ knowledge, skills, and abilities, and uses this to recommend or direct the student toward new curriculum materials. Students could access collaborators in the classroom, or anywhere in the world, through the network to complete learning activities cooperatively — or competitively, in game-based learning models. Conceivably, students could access standards-aligned curriculum any time and anywhere — from home or school. Information and data about student activities and accomplishments would automatically be made available to the teacher and integrated with her data analysis and record-keeping software. This kind of direct access by students and expanded access by teachers to appropriate, curriculum-aligned digital learning materials, as well as to feedback information about student's activities and results, greatly expands the *content density* of the classroom. Again, our view is not that more is necessarily better, but that content density can be increased and decreased to fit the situation.

Time. *Temporal density* is how much activity and communication occurs in a given amount of time and is thus connected to communicative and content density. Time on task is the *sine qua non* of the organization of schools and classroom instruction. Other temporal issues in the classroom include class work flow and individual pace. Lower temporal density occurs when students wait for a turn to ask questions, or wait for the teacher to take roll or pass out materials. High temporal density is when all students are working and communicating. . Automation of routine tasks is one simple example of how temporal density can be increased and "downtime" reduced.

In sum, our framework posits that each dimension or layer can have greater or less density at any point in time, and that the density of each layer is configurable with the aid of technology through social practices and norms. Technology does not determine, but rather facilitates, configuration of the density of each layer. In addition, when the "space" is instrumented — that is, has a classroom network infrastructure with content and services with which students and the teacher interact — data about the configuration of each layer can be easily captured. These data (and syntheses of them) constitute feedback about the system, as well as about the actions and actors within it, which can be used in the moment by students in a self-regulatory manner and/or by teachers to achieve some instructional goal (e.g., to increase motivation, collaboration, or engagement with content). In Figure 2, the middle column lists the "layers" or elements within the classroom space. The left-hand column indicates some approaches by which each of these layers can be optimized through configuration of network settings and features. Finally, the right-hand column indicates the positive student and teacher outcomes that can result from optimal configuration of this space.

ENVISIONING TOMORROW'S DATA-RICH, HIGH-PERFORMANCE CLASSROOM

From the perspective of this framework, we begin to rethink classroom technology (or distributed online networks) as an integrated infrastructure with digital content and services that can greatly empower students and teachers in managing, personalizing, and adapting instructional resources, activities, interactions, and feedback in a way that enhances teachers' instructional practice as well as student learning experiences and achievement. This kind of configurability offers teachers and students many more possibilities for interacting with each other and others outside the classroom. More importantly, the infrastructure can give teacher and students the information and feedback they need to optimize communication and collaboration, so that it occurs among the right people at the right time, around the right content.

Student interaction with content can be personalized, which could go a long way to improving their engagement. One study showed that, at a given moment, 40 percent of students report that their learning activities involve content they already know (Uekawa, Borman, & Lee, 2005). In our classroom study, we saw students who were bored or frustrated because they were receiving content with which they were already familiar. The teachers had difficulty challenging and helping all students at the levels at which they needed to be reached.

Information Feedback and Feed Forward

Teachers' struggles to understand what students know, determine where they need help, and provide appropriate and timely feedback and intervention constitute an area of acute need. In our study, a major theme in teachers' discussion of their out-of-class time was the combined task of creating and grading assessments of different sorts. These teachers see creating assessments as a cognitively demanding task, while viewing grading as primarily procedural. Other areas where teachers expressed a need for more time or the ability to make more efficient use of out-of-class time were in homework grading, preparation of lessons, and performing administrative duties.

The timing of feedback is critical to its value in benefiting student learning (Bangert-Drowns, Kulik, Kulik, & Morgan, 1991). The time pressure to provide feedback was acute for some teachers in our studies, and they used several strategies to render feedback more timely, as we saw above. Teachers' interview comments reflect the benefits they see for providing feedback to students and their frustration about their limited time and resources for doing so:

- [T]he hard thing is if I collect them [homework assignments], more than likely they're not going to be turned back [to the students] the next day, which means [the feedback is] no longer of use to them because it's gone by. It's not the immediate feedback— are they understanding it, are they not understanding it?
- If I want to grade all the things that I wanted to grade daily, I'd be spending two hours a day on top of my prepping and the grading I'm doing already.
- The big ones [stressors] are just being able to get everything graded in a reasonable fashion so that you are able to get them back with immediate feedback.

Given the realities of teachers' workloads, traditional classroom assessment and feedback methods are generally "too little, too late," with feedback coming in the days-long time cycles represented in Figure 3.

Insert Figure 3 about here.

A classroom technology infrastructure has the potential to make rich information on learning, progress, and process variables (including engagement) available to students and teachers in real time. A platform approach in which teachers and students access content and services — which can include group learning activities, complex projects, and automatic scoring of simple and complex performances (Gibson, 2003; Quellmalz & Haertel, in press) — can easily provide instant feedback about multiple performances, events, and processes to both teachers' and students in real time, providing the rapid cycles of feedback represented in Figure 4. For example, as students worked through a set of algebra problems during class, individually or in small groups, a teacher could have real time, easy-to read-display of information about students' progress through the problem set, which ones they did correctly and incorrectly, as well as the ability to view students' work via screen-sharing from their on tablet-type PC. Seeing frequently used incorrect strategy in student's work, the teacher could call the class's attention to the whiteboard for a demonstration of the correct solution steps. When students enter an incorrect solution into their Tablet PCs, they can received an automated response, that says, for example, "That's not correct. Review your solution steps for the error." In this way, students' learning is regulated in real time, which has been shown to enhance learning (Black & Wiliam, 1998; Perrenoud, 1998; Wiliam, 2007). This feedback can motivate students and support teachers' ability to optimize lessons, learning interactions, and classroom processes.

Insert Figure 4 about here.

Personalizing and Differentiating Instruction

The theme of student engagement and participation also has design implications related to the personalization and differentiation of instruction. Among the factors affecting student motivation and engagement, teachers mentioned the individual needs of specific students as well as the need for different types of accountability frameworks. In particular, they talked about:

- **Prior math skills, knowledge, and preparedness**. Students lose motivation to listen to a lecture or work on a problem when they don't understand what is going on or feel they are not prepared to do the work.
- **Accountability**. This is seen as crucial to recruiting students' participation in assignments and classroom activity. Students, teachers said, need to be held accountable, for example, for participating during class and completing in-class work assignment. However, some teachers struggle to establish accountability and gain buy-in from students. One teacher said doing more grading is an expedient way of increasing accountability.
- **Meaningful reasons/goals for learning algebra**. Many students — typically, those who do not plan to go to college — do not see algebra as meaningful.

Thus there is no buy-in from these students to learning algebra.

- **Meaningful tasks/materials.** It is difficult to motivate students to work on materials/tasks that are “dry,” “boring,” or “convoluted.”

Taking these issues seriously leads to the conclusion that classroom technology infrastructure design should allow not only personalization or differentiation of instruction and content but also of the organization of work, accountability, and incentives for completing work. Through a school or classroom network, students could opt to pursue content through a variety of transactional frames, including a points/competition frame or a collaboration/cooperation frame, each of which can be differentially motivating for different students.,

Going forward, we are exploring how rich, intelligent, digital content can be made available as services through networked tablet devices and integrated through a classroom computing *platform* for which the teacher has simple, easy-to-read display that provides decision-support, real-time information suitable for on-the-fly use during classroom activity. In this kind of classroom technology infrastructure, students can access rich, interactive, and complex learning content that integrates automatic scoring and feedback. Information about students’ interactions with this content and with each other would be available to the teacher in real time.

In this vision the teacher is seen as the engineer of the overall learning environment, the orchestrator of learning activity in the classroom. Rich, complex information about not only students’ learning activities but also their social interactions progress could be available to the teacher in real time to use in optimizing individual and social learning processes in the classroom in a longer-term vision, we add the component of helpful, affectively attuned software agents that guide students’ interaction with the content and provide information to the teacher about students’ learning progress (Hamilton, 2004).

To support these kinds of interactions within a networked classroom, a key design principle for the classroom infrastructure should be to enable teachers to orchestrate students’ interaction with content, based on powerful, valid, real-time information. Teachers, for example, could create pairs and small groups to help each other, based on data about students' mastery and progress through the content. Intelligent tutoring systems could be socialized, so that students working on the same content are networked together and able to provide and ask for help based on their interactions with the content proffered. Intelligent tutoring systems can also be repsonive to students' affective cues, (Hamilton, 2004; Kort, Reilly, & Picard, 2001) enabling the construction of a model of a student's affective states. This would enable these systems to provide interaction that supports the students emotion-regulation during their work, enhancing the student's engagement, persistence, and thereby enhancing learning. Information about students' collaboration and communication through this network could also be provided to the teacher. For example, a classroom social network diagram could be produced that shows the teacher which students are giving and providing help, and which students are interacting less; it could also relate social network data learning data. This data could inform a teachers' decisions regarding the formation of heterogeneous groups for small group work and pairing of more- and less-expert peers for collaborative activities. This aggregated information could be available to the teacher in real time, in easy-to-interpret displays. Teachers can use information from intelligent systems about students' progress and results with instructional materials, as well as social interactions, to orchestrate the classroom, optimizing learning activities, instruction, interactions, groupings, and classroom processes *during* instruction, after class, and at any other time.

The kind of instrumented classroom we envision is quite different in scale, scope, and purpose from the technologies and assessments currently being advanced under the rubric of DDDM. Our platform would enable more diagnostic, real-time assessment for decision-making on the fly. The kinds of assessment data yielded would not be limited to those that can be gathered from students working independently to complete multiple-choice tests. Instead, a multitude of complex skills, including students' abilities to collaborate with a diverse array of peers, can be assessed rapidly and easily. Further, and perhaps most important, such a platform recognizes the realities of classroom life and its demands for efficiency while empowering the teacher to be an effective clinician, diagnosing individual student difficulties for the purpose of successfully reaching all students in class.

This kind of classroom, furthermore, goes much further toward advancing the goal of creating assessments that are diagnostic and case-based, as Confrey (this volume) argues is necessary for a fair and valid testing system. Classrooms that are cognitively dense would provide teachers with a wide array of occasions for capturing what students know and can do in specific topic areas, something that classroom demands on teachers' time makes difficult today. Similarly, the kinds of individualization afforded by new networked technologies, including personalization of opportunities for collaborative learning from peers, enable teachers to act on diagnostic information on a case-by-case basis. Finally, the immediate integration of data into longitudinal systems allows for both short-term and long-term use to guide instructional decision-making in the moment or at the end of the week, unit, semester, or year. Such a vision may indeed be challenging to realize, but the importance of the need and the demonstrated promise of existing technologies suggest that the vision is realizable and that pursuing the creation of data-rich classrooms for tomorrow is a worthy goal.

FIGURES

Figure 1. Research Design and Methods.

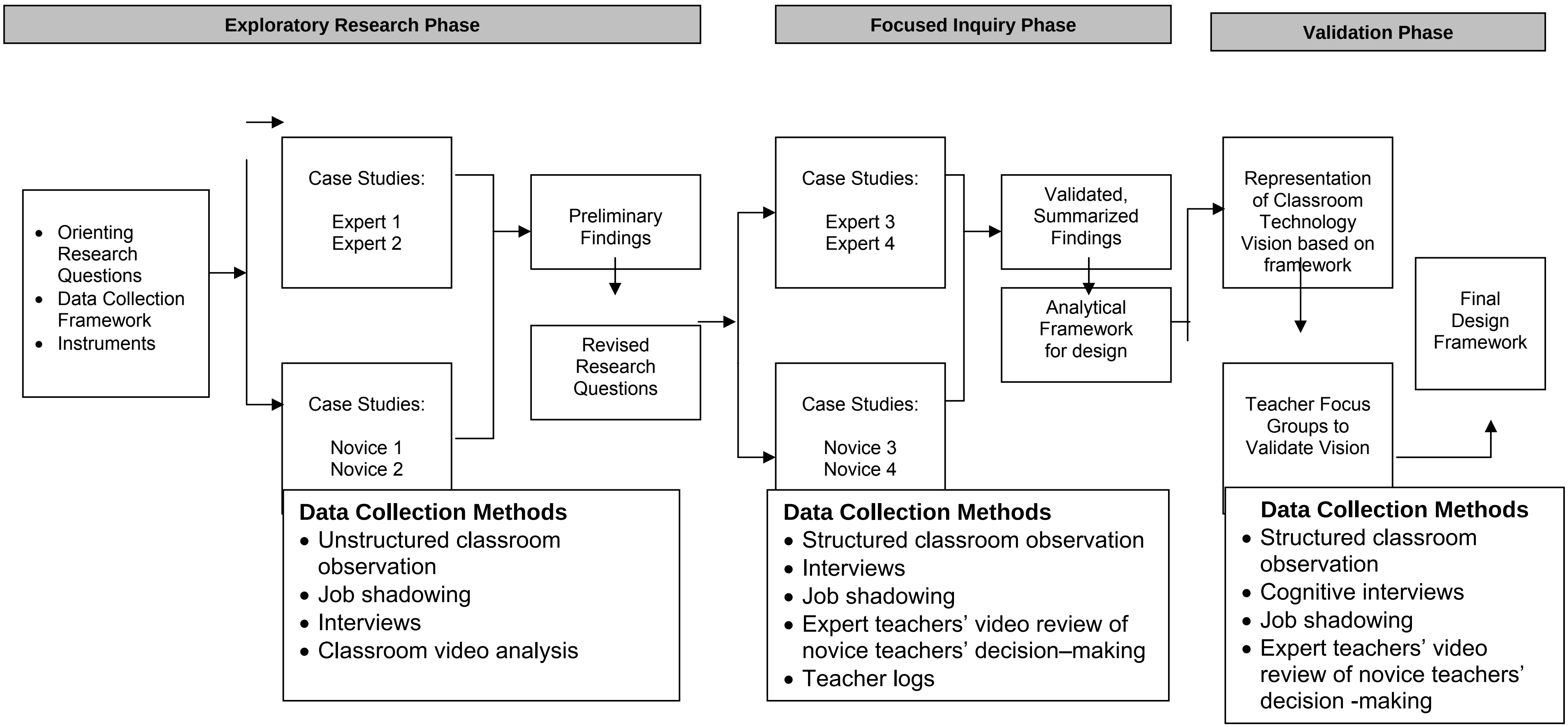


Figure 2. Analytical Framework to Inform Technology Design for the Classroom as a Socio-Cognitive System.

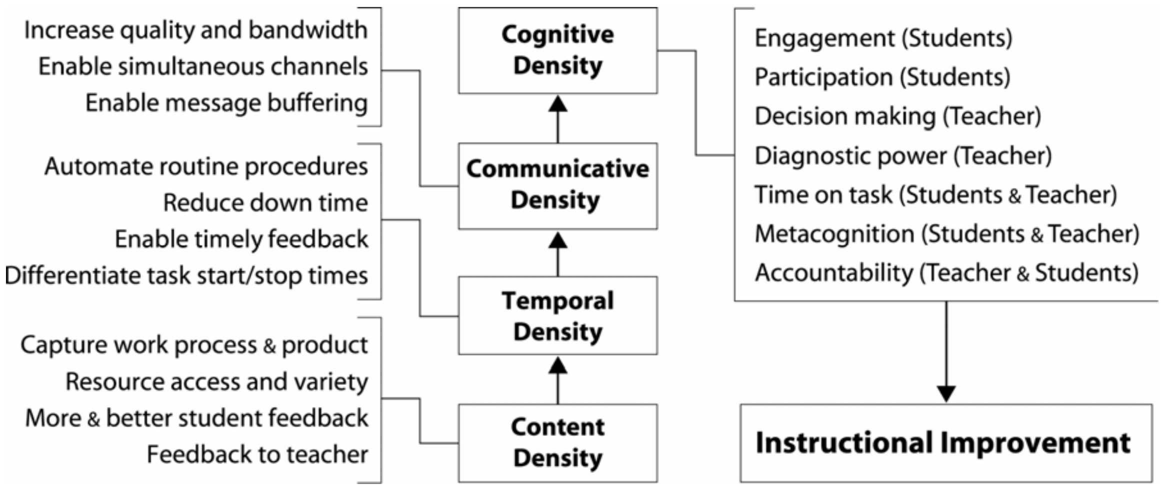


Figure 3. Time Lapses in Feedback to Students in Traditional Classrooms.

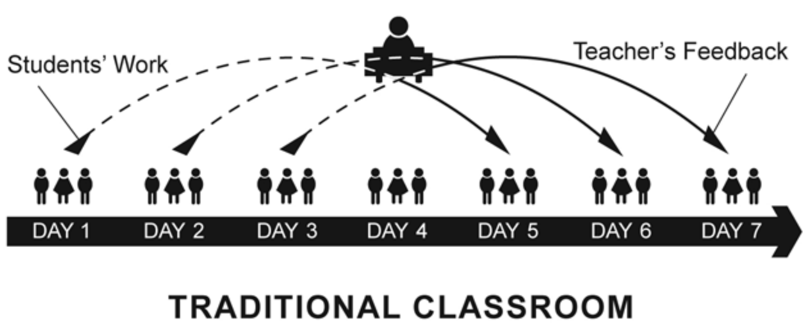
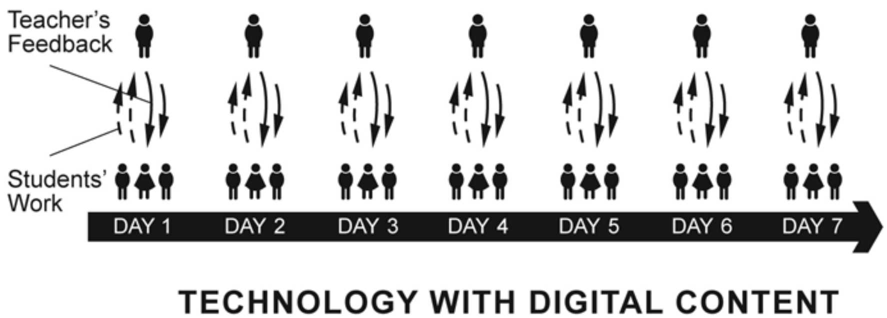


Figure 4. Rapid Cycles of Feedback to Students in Classrooms with a Technology Infrastructure.



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