

ELECTRONIC ARTICLE

A Conceptual Framework for Digital Libraries for K-12 Mathematics Education: Part 2, New Educational Standards, Policy Making, and Accountability¹

Hsin-liang Chen² and Philip Doty³

This paper is the second of two (see pt. 1) that describe a six-part conceptual framework for designing and evaluating digital libraries for mathematics education in K-12 settings: information literacy, information organization, integrated learning, adoption of new educational standards, integration of pertinent changes in educational policy making, and ensuring accountability. This second paper explores the final three elements of the six-part framework. Accountability has become the core of the educational reform initiated by federal policies and measured by state-mandated educational standards. These political circumstances, as well as communication and collaboration, must be constitutively involved in the iterative design, implementation, and evaluation of digital libraries. The paper concludes with a series of recommendations for the design and implementation of digital libraries for K-12 mathematics education based on the authors' discussion of these final three elements.

Introduction

Most work in the design and implementation of digital libraries tends to emphasize retrieval algorithms, information management, or collection development. This paper, in contrast, is the second of two to explore a six-part conceptual framework for developing digital libraries (DLs) for K-12 mathematics education that emphasizes communication, collaboration, and the overall context of digital libraries. Figure 1 illustrates the full six-part framework: information literacy, information organization, inte-

1. We would like to thank Angela Valenzuela, Danielle Plumer, and others for helpful comments on earlier drafts of this and the companion paper.
2. Assistant professor, School of Information, University of Texas at Austin, 1 University Station, D 7000, Austin, Texas 78712-0390; E-mail chen@ischool.utexas.edu.
3. Associate professor, School of Information, University of Texas at Austin, 1 University Station, D 7000, Austin, Texas 78712-0390; E-mail pdoty@ischool.utexas.edu.

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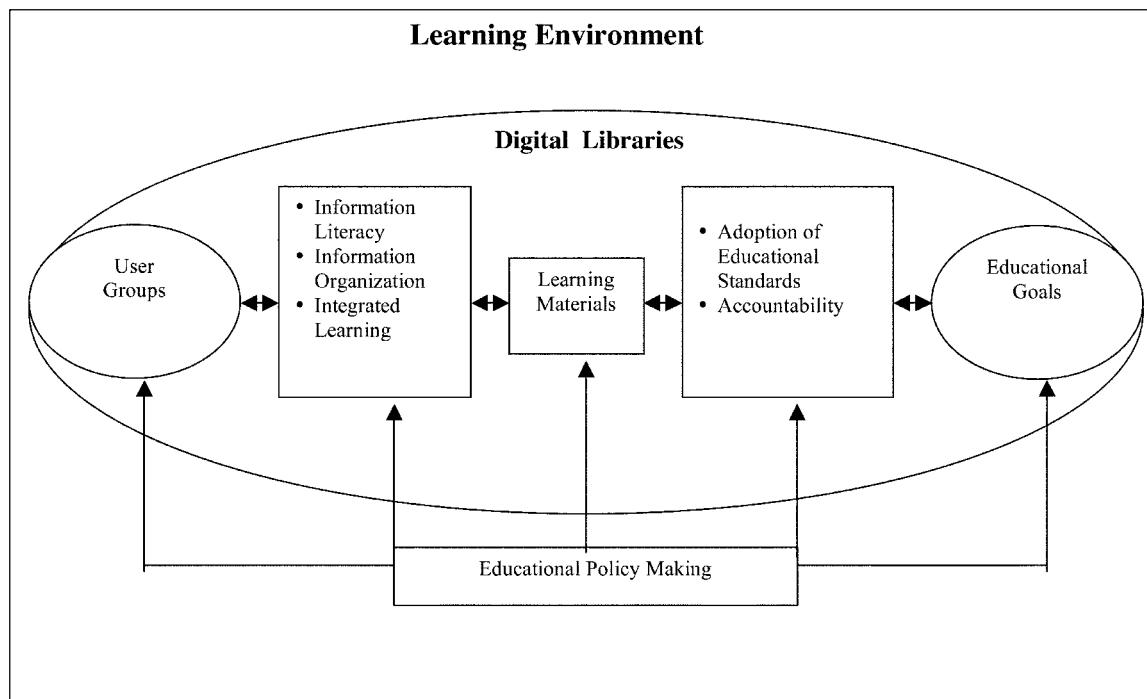


FIG. 1.—The six-part framework

TABLE 1
RECOMMENDATIONS FOR THE DESIGN OF DIGITAL LIBRARIES IN PART 1

Characteristics of Successful Digital Libraries for K-12 Math Education
Different indexing mechanisms, some aligned with educational standards
Access to synonyms, some also linked to educational standards
Range of resources with regard to difficulty and learning capability, also calibrated with educational standards
Multiple retrieval mechanisms and interfaces
Text as well as multimedia sources
Ability to create and manipulate objects online
Information visualization functions
Ability to reflect on learning and create narratives
Support of exploratory learning and open inquiry

grated learning, adoption of educational standards for K-12 math learners and teachers, educational policy making, and accountability for achieving the goals of K-12 math education. Among other things, this integrated model indicates that realistic and responsive policy making must support the development of subject standards by professional associations of classroom teachers. Well-organized digital libraries in turn support the development and expression of information literacy and enhance integrated learning as discussed in part 1 of this series of two papers. The subject standards developed by teachers must also help learners and teachers connect local social and learning practices to the standards and are important means of achieving this integrated vision. Table 1 summarizes the recommendations made in part 1, which, in concert with the recommendations developed in part 2 (see table 2 in “Recommendations” below), aim to move beyond the reductive maxims and technological determinism that animate too much digital library research and commentary.

This paper focuses on the final three elements of the conceptual framework. We can consider these elements (educational standards, policy making, and accountability) as part of the web of social and material relations that are the basis of sociotechnical analysis [1, p. 1]. Thus, the full six-part framework can be informally described as a sociotechnical analysis; this point is explored further in the conclusion. More specifically, this paper discusses new educational standards for K-12 mathematics education developed by professional associations of classroom teachers and the need to adhere to such standards while still responding to classroom-based assessment, as well as local pedagogic practices, social networks, vocabularies, “indigenous” mathematical literacies, and negotiated meanings. Although high-stakes tests are supposed to be grounded in such standards, these tests are very poor means for determining students’ abilities to perform to those subject standards [2]. We discuss these and other topics in the

section on policy making. The final part of the framework is ensuring pedagogic and political accountability to many of the constituencies important to K–12 education: learners, their parents, teachers, school and district administrators, policy makers, and others. Accountability must include responsiveness to, and enhancement of, local literacies, vocabularies, work practices, social networks, and other elements important to successful education. Concerns with equity, reflexivity, and narrative in the classroom for teachers and learners, and formative evaluation also animate the discussion of stakeholders and accountability. The paper concludes with recommendations for the design, implementation, and evaluation of digital libraries for K–12 mathematics education. The recommendations in parts 1 and 2 are offered with the clear proviso that any list of generalized rules of thumb and axioms are “incompatible with a situated approach to social research” [1, p. 19]. The authors aim to avoid such totalizing mistakes by consistently emphasizing the import of local circumstances and the need to adapt digital libraries to those circumstances. This attitude also rests firmly on a commitment to the naturalistic study of users and their complex and highly situated behaviors.

As discussed in part 1, numeracy includes at least three modes of communication and reasoning that help us describe real-world situations, to ourselves and others, and to understand these situations more fully [3–9]:

- Learners must be able to generate verbal descriptions of real-world situations and the appropriate mathematical concepts and relationships they involve.
- Learners must be able to use software, paper and pencil, and other graphic tools to generate pictures of the situations and to demonstrate the most important relationships among their component parts.
- Learners must demonstrate an ability to use the right sorts of formulas, definitions, and other generic mathematical tools to describe the situations and address them mathematically.

These modes are not mutually exclusive, and situations and circumstances dictate which ones may be most valuable at any time. These three goals far surpass simple calculation. They involve mathematical reasoning and the actual doing of mathematics, not simply witnessing what others do mathematically. Digital libraries meant to support K–12 mathematics education must help learners develop these multiple literacies. The proposed six-part conceptual framework is intended to provide guidance to the (iterative) design, deployment, and use of such DLs. The paper first discusses the development of new standards for mathematics education and how they can inform DLs for math education.

Adoption of New Standards for Mathematics Education

For good and for ill, standards have become a central concern of governmental agencies and researchers when discussing education reform in the United States. We, like many commentators (e.g., [10, 11]), doubt the pedagogic and political wisdom of a standardized-test approach to education. Standards developed by local teachers and classroom teachers' organizations, however, are key to domain competencies [1]. In such a climate, American mathematics education needs to develop new standards for information literacy and digital tools such as computer-aided instruction (CAI) software and multimedia programs. Although math teachers and researchers are still debating the credibility and effectiveness of CAI programs for learning mathematics, it is obvious that computer-based instructional programs have spread rapidly and without much, if any, standardization in interfaces or objectives.

The information literacy approach helps learners become active and responsive locators, evaluators, users, and creators of learning materials related to mathematics—to address problems and satisfy their own learning paces and abilities. Without the personal appropriation allowed by extended (collaborative) projects and inquiry-based learning, mathematics education and the use of digital materials in math education are not likely to achieve their goals [12] and will likely fall prey to the centralizing and totalizing errors of intrusive design maxims and axioms warned of throughout *Digital Library Use* [1]. Active learning is key to addressing some of the important difficulties that teachers, researchers, and policy makers face in integrating digital technologies into mathematics education, as well as into the curriculum more generally [13].

Looking closely at the standards for mathematics education in K-12 settings developed by the National Council of Teachers of Mathematics (NCTM) can help us see more clearly how well-conceived, well-designed, and well-implemented digital libraries can help users to achieve significant improvements in mathematics education. These standards are from *Principles and Standards for School Mathematics* and identify important mathematical concepts and processes in prekindergarten through grade 12 [14].

The NCTM standards begin with principles related to six significant areas of mathematics education applicable to all age and grade levels:

1. Equity—there must be sufficient support and high expectations for all students.
2. Curriculum—math curricula must be coherent, focused on important elements of mathematics, and coordinated across grades.
3. Teaching—good mathematics teaching is based on teachers' knowl-

edge of mathematics, subject standards, and students' needs and abilities.

4. Learning—students must be active learners able to bridge old knowledge to new.
5. Assessment—assessment must be used to encourage learning, especially by indicating where students need further development.
6. Technology—appropriate technologies of all kinds must be integrated into mathematics curricula across grade levels.

The NCTM [14] and Thomas Rowan and Barbara Bourne [9] offer a more complete discussion of the standards and their history.

The NCTM also includes five “content” and five process standards in their guidelines for pre-K to grade 12 mathematics students. Like the principles listed above, these content and process standards are “broad, far-reaching goals that establish a direction in which [math] education should point” [9, p. 8]. The list here indicates some of the major emphases of the five content standards:

1. The Number and Operations Standard aims to help students understand numbers, especially how to represent them and their relationships.
2. The Algebra Standard’s goals include helping students to “represent and analyze mathematical situations and structures using algebraic symbols” and to generate mathematical models of problems [9, p. 9].
3. The Geometry Standard emphasizes the analysis of two- and three-dimensional geometric shapes, the development of arguments about geometric relationships, and how to “use visualization, spatial reasoning, and geometric modeling to solve problems” [9, p. 9].
4. The Measurement Standard aims to help students, among other things, to understand objects’ measurable characteristics and how to measure them.
5. One of the major goals of the Data Analysis and Probability Standard is to enable learners to “formulate questions that can be addressed with data and collect, organize, and display relevant data to answer them” [9, p. 9].

There are also five process standards in the NCTM typology. As with the content standards listed above, this list highlights only some of the many goals of these standards:

1. The Problem Solving Standard helps learners develop new knowledge about mathematics and problem solving using a variety of strategies, while also emphasizing self-conscious reflection about mathematical reasoning.
2. The Reasoning and Proof Standard aims especially to enable students

to develop, evaluate, and use different types of mathematical arguments and proofs.

3. Among other things, the Connections Standard enables learners to understand how mathematical ideas are connected and can be applied to various situations outside of the formal study of mathematics.
4. The Representation Standard's goals include helping students to develop, represent, and communicate mathematical ideas and to "use representations to model and interpret physical, social, and mathematical phenomena" [9, p. 10].
5. The Communication Standard is particularly important to the use of digital libraries in mathematics education and to the thrust of our framework, which emphasizes digital libraries as communicative media, and for that reason we list it last, rather than third, as it is in the standards themselves. Rowan and Bourne [9, p. 10] enumerate all of its parts here, quoting the NCTM. This standard aims to help students to
 - organize and consolidate their mathematical thinking through communication
 - communicate their mathematical thinking coherently and clearly to peers, teachers, and others
 - analyze and evaluate the mathematical thinking and strategies of others
 - use the language of mathematics to express mathematical ideas precisely.

These principles and standards emphasize four activities essential to mathematical success: reasoning, representation, collaborative learning, and communication. Such activities are dependent on information organization, information literacy, and integrated learning environments, the first three parts of our framework for DLs in mathematics education as discussed in part 1.

Artemis, the interface that students and teachers use to interact with the Middle Years Digital Library (MYDL), developed by the Center for Highly Interactive Computing in Education at the University of Michigan, features magazines, science and mathematics reference tools, and an integrated set of resources identified and "catalogued" (their word) by the MYDL Web librarians according to reading level and students' learning needs, as well as topic [15]. Math and science students can complete searches much like they can in other digital library environments, but Artemis provides major vocabulary and communicative functionalities that are rare in digital libraries (see fig. 2):

- It provides "Alternatives" that offer searchers other possible search fields for the keywords used in searches.

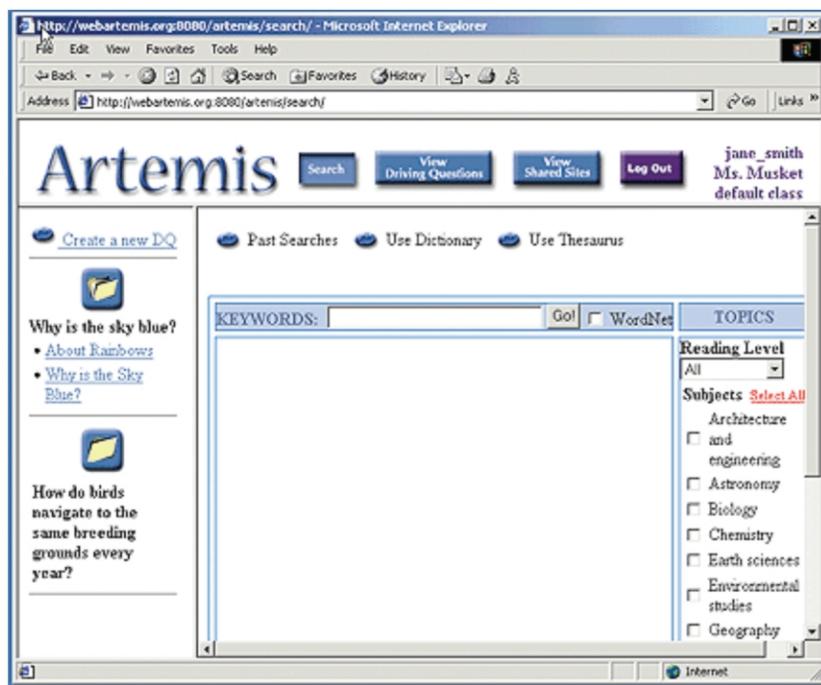


FIG. 2.—Artemis from the Center for Highly Interactive Computing in Education [15]

- It allows students to save useful sites in a separate folder (Cool Sites) that can then be shared seamlessly with classmates and teachers.
- It displays the user's history of past searches from a pull-down menu that includes results from those searches; like current searches, the results of these past searches can also be easily shared with others.

These communicative and vocabulary functions are key to the success of DLs generally, but especially in mathematics education.

Tying content standards to digital library materials is being taken further still by a cooperative project involving the National Science Foundation's National Science Digital Library (NSDL), discussed in part 1. The project is entitled Standard Connection: Mapping NSDL Educational Objects to Content Standards. The coinvestigators are Stuart Sutton at the University of Washington, Liz Liddy at Syracuse University, and John Kendall at Mid-Continent Research for Education and Learning in Colorado. Using Natural Language Processing techniques, the project aims to assign metatags to resources as they are added to the NSDL that "indicate the educational content standard(s) for which each item serves as a learning resource" [16].

Educational Software Components of Tomorrow (ESCOT) has devel-

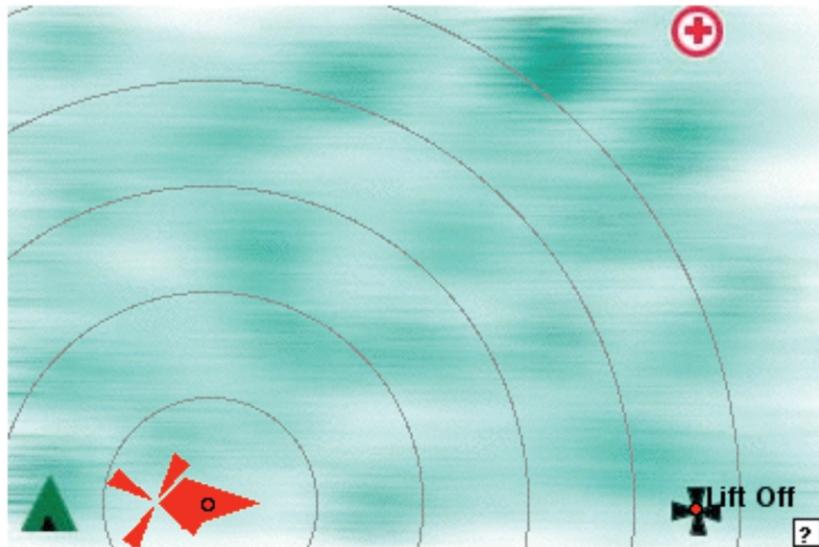


FIG. 3.—Search and rescue paths from ESCOT (Educational Software Components of Tomorrow) [17].

oped an application called Search and Rescue Paths, which is explicitly tied to several of the NCTM standards: geometry (students must “use visualization, spatial reasoning, and geometric modeling to solve problems”); measurement (they must “apply appropriate techniques, tools, and formulas to determine measurements”); problem solving (students must “solve problems that arise in mathematics and in other contexts”); communication (learners must “communicate mathematical thinking coherently and clearly to peers, teachers, and others; use the language of mathematics to express mathematical ideas precisely”); and connections (students must “recognize and apply mathematics in contexts outside of mathematics”). As figure 3 illustrates, Search and Rescue Paths helps students understand the concepts of degrees and angles in a circle, direction, and way finding, by using the metaphor of a search-and-rescue operation by helicopter [17].

Developers of digital libraries for mathematics education, as well as mathematics teachers, must put emphasis on these four activities discussed in Rowan and Bourne [9]: reasoning, representation, collaborative learning, and communication. Unfortunately, digital library research and implementation have, instead, tended to emphasize only retrieval algorithms, collection development, and the like. While these elements of digital libraries are important, they are insufficient to ensure digital libraries’ suc-

cess in educational environments [18]. The final two parts of our six-part conceptual framework, reactions to important changes in educational policy making and ensuring accountability, are further keys to the success of digital libraries in mathematics education.

Integration of Initiatives in Educational Policy Making

Conceptually, one way to connect the top-down and sometimes remote world of education policy making with local, classroom-based instruction is to consider digital libraries as mediating institutions. That is, DLs are bridges between government and citizens, like civic institutions (e.g., schools, libraries, and community groups), social organizations (e.g., Rotary clubs, academic sororities, and athletic teams), and others. The renewed interest in civic society and in enhancing and understanding the many ties that bind us together can be reflected in how we connect educational policies with DLs deployed in schools.

New standards for mathematics education developed by experienced classroom teachers and researchers need the support of policy makers, for example, the U.S. National Science Foundation's National Science, Mathematics, Engineering, and Technology Education Digital Library, mentioned in part 1 [19]. Since new standards, when used appropriately, are essential to the enhancement of the quality of mathematics education, policy makers must recognize the position of the kinds of new standards in mathematics education discussed in the previous section. In the case of Civics Online [20], we can see an integration of policy making, educational standards, curriculum development, and creation of learning materials implemented in the state of Michigan, with a special sensitivity to terminology (see pt. 1). Good policy helps provide a structure for the evaluation of students' performance while allowing sufficient flexibility for adaptation to local circumstances, needs, and interests, especially local literacies and vocabularies [21].

Policy making for mathematics education, whether in governmental or private organizations, is especially volatile in the U.S. now. Federal and state governments, private organizations, professional associations, and other enterprises are engaged with questions of education quality to an extent they have rarely been in the past. They are also engaged with the development and deployment of education-specific digital tools and are committed to the development of new and (sometimes) revolutionary policy initiatives. Unfortunately, bad policy instruments, especially those that are top-down and that contribute further to inequity and underachievement, also abound. Education reform was one of U.S. President George W. Bush's major campaign themes in the 2000 election. He signed his

education reform bill, the No Child Left Behind Act of 2001, into law on January 8, 2002 (Public Law 107-110, 115 *Stat.* 1425). According to the act, public school testing from grades 3 to 8 will be mandatory, thus announcing a new era of public education in the United States. This law and related initiatives signal increased federal involvement in schools and an unprecedented expansion in the role of standardized testing in K-12 education.

As noted in part 1, K-12 public education has traditionally been a highly local concern in the United States. The Bush administration faced considerable opposition from some members of the Congress, educators, local governments, and parents during the passage of the No Child Left Behind Act. That opposition will be an essential part of the context in which the act is implemented and evaluated in the coming months and years, especially as the Congress faces the decision of authorizing funds to implement the act rather than simply expressing support for its principles. How can and should DLs respond to this sort of political initiative? The answer to this question is illustrative of the many challenges that educational digital libraries and their users, designers, and evaluators must address. Digital library research and implementation must (continually) determine how to balance such large-scale policy concerns with local interests, values, and practices.

Other overarching policy initiatives that have important implications for digital libraries in all settings are those dealing with so-called intellectual property, especially copyright, privacy, and public/private partnerships. For example, the Technology, Education, and Copyright Harmonization Act, the so-called TEACH Act, is intended to make it easier for teachers and other educators to claim fair use (a defense against a charge of illegal taking of copyrighted material) in the digital distribution of audio recordings, dramas, and other performative, nontextual materials. This bill was signed into law as part of H.R. 2215 authorizing Department of Justice appropriations on November 2, 2002 (Public Law 107-273, 116 *Stat.* 1758). The law is dense, unclearly written, and is difficult for nonexperts to read, much less adhere to. Further, while offering more freedom to distance educators using digital materials under copyright, the law also has rigorous requirements for teachers, information technology professionals, and institutional policy makers, for example, the development of explicit and consistent institutional policies for the use of copyrighted materials.

In each session of the Congress, dozens of intellectual property bills with important implications for digital libraries are introduced. Some of those bills, if passed into law and signed, can provide new opportunities for the implementation of multimedia digital libraries for educational use. Others would sharply delimit such implementation. Still others would do both. Designers and implementers of digital libraries must know the law, must provide guidance to teachers and students about what is and what is not

ethical and legal in the use of digital material, and redesign and reimplement the DLs as the law evolves. For example, many educational institutions are aware of the need to be responsive to the evolving copyright context in their design and use of online materials, offering comprehensive guidelines to their faculty, staff, and students. An outstanding and widely used example is Georgia Harper's Copyright Crash Course [22] for the University of Texas System. Chapter 1 of Mary Minow and Tom Lipinski's *The Library's Legal Answer Book* is also clear and very useful for understanding the evolving copyright context in which DLs exist [23].

Considering What "Policy" Is

In ordinary discourse, the term "policy" means either a formal directive for organizational behavior and/or the documents that express that directive. In the context of more formal policy studies, however, looking more carefully at the term is useful. Unfortunately, such an effort is often frustrated by the fact that the uses of the term vary so much [24, 25]. While we cannot explore these concepts and difficulties in any depth, we can outline the most fundamental fracture in the identification and analysis of policy. The "traditional" stance, well-grounded in political science and policy analysis, asserts that public policy is "whatever governments choose to do or not do, that is, government action and inaction" [26, p. 2]. Similarly, this approach asserts that policies are "pragmatic, action-oriented" solutions to fundamental social problems [27].

Theorists and practitioners of policy analysis have generated a useful alternative conceptualization of public policy that emphasizes power relations, value conflicts, learning, and context, especially critiquing limited, functionalist "definitions" of policy and the so-called problem-solving approach (e.g., [28–31]). E. S. Overman and Anthony Cahill [32, p. 804], for example, assert that "policy formation is the process of working within a normative structure to resolve value conflicts," while Mark Considine says that "policy is the continuing work done by groups of policy actors who use available public institutions to articulate and express the things they value" [33, p. 4].

David Levy, with others like Langdon Winner, pointedly reminds us that determining and supporting values cannot be merely ancillary to the design and implementation process for digital libraries [34, p. 25]. Instead, social context and values must be integrated with the iterative design, deployment, and evaluation of DLs. This is especially true in education. So, given the traditional and alternative perspectives on what policy is, we can offer a working definition of the term "policy" for the purposes of our discussion of K-12 mathematics education: the commitment of public and/or organizational resources to certain courses of action to achieve certain goals, using democratic values such as wide participation and transparency, and

encouraging the processes of reflective negotiation and learning in the context of differential power and value conflicts of all kinds. Such an orientation leads us to two important considerations: (1) assessment of educational success, especially high-stakes standardized testing, and (2) the final part of our six-part framework—accountability.

A Brief Word on High-Stakes Standardized Testing

As is widely recognized, the 1983 publication of *A Nation at Risk* [35] and *Educating Americans for the Twenty-first Century* [36] were landmarks in turning public attention to the quality of K-12 education in the United States, especially in the public schools, and to its many weaknesses. These reports were followed by the 1989 Governors' Mathematical Education Summit. The first wave of reactions to these and related events were largely top-down efforts that emphasized what we now call high-stakes testing in public schools. For example, as early as 2001, forty-nine states mandated testing of students, and all of them tested mathematical ability [37].

In the late 1980s, however, change in educational policy began to appear at the state, local, and school campus levels, with a growing emphasis on performance-based assessment [38]. These second-wave efforts focused especially on the development of statewide standards for education in many subject areas. Unfortunately, local and state subject standards, curricula, and practices, many of which are superb, have rarely been linked to the (usually multiple choice) tests meant to test academic achievement. Instead of testing what is taught, we are teaching what is tested [39, pp. 97–111], eliminating local initiative and creativity and achieving standardization, not educational standards [2]. As many commentators have pointed out (e.g., [10]), this approach is of limited value. John Merrow says that we are “virtually abandoning the curriculum” [11, p. 1] and further argues that difficulties with math education are, in fact, not a national problem. Instead, we face an unpredictable patchwork of schools, districts, states, and regions that are high-performing on any particular criterion mixed with schools, districts, states, and regions that cannot reach any desired level of achievement. Examples of the inability of current, high-stakes, multiple-choice tests to adapt to local circumstances, especially to local literacies, language communities, cultural subgroups, and work practices, abound. It is also plain that such testing has reasonable and important advocates who insist that it is essential to educational performance and achievement.

One of the major weaknesses of high-stakes, multiple-choice standardized tests for academic achievement is their emphasis on skills and computation. While such an emphasis is an artifact of the format of the tests and of the emphases of American mathematical education, standardized testing also cannot measure the ability to reason mathematically or stu-

dents' ability to think critically about mathematical topics (e.g., [9]). Good mathematical subject standards, developed by skilled classroom teachers and their professional associations, focus on helping students to "value mathematics, be confident in their own abilities, be mathematical problem solvers, and communicate and reason mathematically" ([9], p. 11). Standardized tests clearly cannot identify nor measure achievement related to locally and professionally developed standards, practices, and social networks.

As discussed above in the section on subject standards, the National Council of Teachers of Mathematics has been among the leaders in the development of important policy initiatives for mathematics education [14]. The best of these, as with other standards for education, often adhere to principles that Jerome Bruner, in particular, has established for educational excellence. One need not support (the early) Bruner's more behaviorist and cognitivist ideas to recognize the value of these principles for the design and implementation of digital libraries for K–12 mathematics education, for example, an emphasis on key ideas rather than ephemera of each subject area; inductive learning; and structured "revisits" to older material that reemphasizes the important elements of what has already been learned and the chief connections between that material and new knowledge. Bruner has called this approach, among other things, a "spiral curriculum in which ideas are first presented in a form and language, honest though imprecise, which can be grasped by the child, ideas that can be revisited later with greater precision and power until, finally, the student has achieved the reward of master" [40, pp. 107–8]. These revisits or spiral curricula are akin to Lev Vygotsky's concept of scaffolding as described by David Wood, Bruner, and Gail Ross [41] whereby, among other things, teachers help students build self-conscious and explicit bridges to new competencies from their existing understandings.

Social capital can help us identify one of the particular concerns with the implementation of educational policy directives. Among the most important elements of a teacher's repertoire are existing knowledge, the ability to apply such knowledge to a variety of situations, and the ability to help students understand how to do the same. Perforce, digital libraries for education involve the burden of asking teachers to lose some of the considerable social capital they have spent many years developing as these teachers develop new areas of expertise in mathematics and in its pedagogy. But, because digital libraries offer unprecedented communication and collaboration capabilities, digital libraries for math education can enhance, not simply undermine, the social capital teachers have already developed in and across schools and disciplines.

For example, James Pellegrino and colleagues, in the context of their policy recommendations, assert that "federal agencies and private-sector

organizations concerned about . . . assessment should support the establishment of multidisciplinary discourse communities to facilitate cross-fertilization of ideas among researchers and assessment developers working at the intersection of cognitive theory and educational measurement” [42, p. 304]. This recommendation, well-grounded in the report as a whole, reminds us clearly that formation of appropriate policy to enhance K-12 mathematics education is complicated by a wide variety of factors. Such factors include the relationships among various levels of government, the highly local character of schools, the necessity of policy implementation in the classroom, the necessity of recognizing classroom practice in policy formation, relationships among educational standards (on the one hand) and teaching and learning practice (on the other hand), and the evolving nature of our understandings of cognition, assessment, and learning. These understandings highlight the social context of learning, communities of practice, and the constitutive character of communication to learning and to the formation of communities. The implementation of digital libraries should address all of these key factors and be created on an explicit and widely accepted social foundation. This imperative, in turn, leads to the final part of our six-part, holistic model: accountability.

Ensuring Political and Pedagogic Accountability

Accountability is an important component of federal education reform as well as that of the states. Many people agree on the importance of linking evaluation of education with stricter accountability even though the forms such evaluation may take, for example, high-stakes testing, are controversial. To ease the tension of controversy, some groups have begun to link accountability to standards and the policies driving mathematics education, especially when those standards are designed, tested, and redesigned by subject-expert classroom teachers. Teachers’ professional associations, at both the federal and state levels, have been among the leaders of this movement. Measurement of students’ performance is best derived from holistic approaches to measuring whether students achieve the goals of explicit, widely supported, but still local, standards for mathematics education that such associations have been developing. Civics Online [20], discussed in part 1, is a good example of such an integrated approach. Its seamless but clear integration of concepts, terms, powerful digital functions, and statewide educational standards, developed by professional associations of classroom teachers, is exemplary.

Standards and Accountability

When used appropriately, standards developed by subject specialists help

students learn, teachers teach, and parents monitor their children's progress. The standards may also enable school administrators to manage the entire process more effectively. One major difficulty is that the use of digital tools, however, may demand longer-term and finer-grained assessments that are able to detect (subtle) changes in thinking or identify rare, but profound, learning events [43]. Assessments are discussed more fully below.

It is important to recall that accountability for the performance of digital libraries for K-12 mathematics education must support the three modes of communication discussed in part 1: the self-generated and informed use of (1) appropriate mathematical words/concepts, (2) pictures, and (3) figures/formulas to understand and describe real-world situations. Further, as mentioned above, these DLs must support and give students the ability to reason, represent, collaborate, and communicate with each other, their teachers, their parents, and others involved in the educational enterprise.

Merrow [11] emphasizes the importance of the hierarchy of accountability that we observe in education today. As we know, teaching is a highly localized practice, and the criteria and reference groups that matter most to teachers are also highly localized. In roughly descending importance, K-12 educators usually think of themselves as accountable to their students, themselves, their students' parents, their fellow (in-school) teachers, their principals, teachers in other schools, and only then to districts and to state and federal policy makers. Without the transparency, realism, flexibility, and multiple criteria discussed above, educational policies, and the use of digital tools in education, no matter how well intentioned, are likely to fail. Good standards take advantage of teachers' self-referential professional behavior [30] in many ways, particularly by encouraging reflexivity in the classroom for teachers and students. Among the important approaches to helping further develop and use reflexivity in the classroom are the following:

- While using classroom teachers' advice and guidance, allowing students to identify what they want to learn, relying on their existing knowledge, mathematical literacies, social networks, shared cognitions, and interests [21, 44, 45]. Such a perspective motivates students and, naturally, can increase their commitment to instruction and to the academic success of their classmates [46].
- Encouraging teachers, both individually and through their disciplinary and professional associations, to help develop subject-specific, rigorous educational standards [37].
- Using multiple metrics for evaluating students' and teachers' performance, including local work-arounds and embedded social and pedagogic practices (e.g., [11, 42, 46]).
- Most important, emphasizing that communication and collaboration

may be the most important functions that robust digital libraries provide, not the simple retrieval of materials.

June Fuller [46] reminds us that support and training of teachers, especially ensuring that they have the time and preparation to take advantage of professional development opportunities, explicitly link policy initiatives (including educational standards) with political and educational accountability.

Judith Mathers and Richard King [38, pp. 3ff.] describe four elements of accountability: (1) standards and assessment, (2) use of multiple indicators, (3) rewards, and (4) sanctions. They explain that, as of 1999, three states developed educational initiatives that had none of these elements, ten states had them all in one form or another, and the remaining thirty-seven had initiatives somewhere between the two extremes. What many educational researchers have made clear, however, is that external and top-down standards of accountability for teachers' performance generally operate at the margins because local, school-based criteria matter most. Teaching, like most forms of practice, is highly localized, contingent, and situated. Thus, those educational policies aimed to "revolutionize" education at the state or federal level rarely penetrate to the level of the local school except through the distorting and punishing lens of high-stakes testing. Instead, accountability for educators, particularly classroom teachers, must meet three criteria: they must be constructive and effective, not destructive; they must be clearly and explicitly linked to students' achievement; and they must be financially realistic [38]. Such localized and subtle analysis holds the best promise to increase the accountability of schools and to increase educational achievement, especially that achievement meant to be enhanced by digital libraries.

Assessments, Incentives, and Equity

Based on a substantial empirical investigation, Carolyn Haug [10, p. 19] concludes that relying on high-stakes tests that use multiple-choice items to measure students' standards-based achievement "may send mixed messages to teachers, students, and parents about what is important." In the context of testing mathematical achievement, such reliance appears to emphasize only computation. Further, these tests report scores only in reference to the performance of other students rather than in reference to how students have performed as compared to the appropriate educational standards. The DLs that encourage and demonstrate collaboration, mathematical reasoning, and reflexivity are better demonstrations of students' learning and teachers' and schools' success. High-stakes educational testing identifies only what students do not know (an especially limited form of summative evaluation)—it does nothing to help remediate such difficulties (formative evaluation).

It is here that digital libraries for K–12 mathematics education and information literacy have significant contributions to make. Teachers can use in-class curricula and assessments implemented in robust digital environments to help determine explicitly how students compare to state and other educational standards, while documenting students' progress, continuing difficulties, and strategies for overcoming obstacles. This type of integrated documentation from rich data streams generated by students in the classroom, however, gives rise to serious concerns about the increased need for privacy, confidentiality of educational records, and the ability to expunge elements of students' records as they mature ([42, p. 287]; also see [47] on the use of documentation and archiving as a fundamental technology of social control and normalization). Related concerns are the reliability and validity of such data.

The 2001 National Research Council Report edited by Pellegrino and colleagues is useful here [42]. While we cannot discuss the report in depth, the report underscores several assessment themes important to our discussion of K–12 mathematics education, information literacy, and digital libraries:

- The importance of multiple measures of students' competencies, especially the recognition of "a broader repertoire of cognitive skills and knowledge" [42, p. 263]
- The primacy of classroom-based assessment
- The need for assessment to give insight into practice, especially the practice of learning communities and not simply the practice of isolated individuals
- The quality of data used for assessment
- The utility of assessments by oneself and one's peers
- The importance of assessing metacognition
- The need for immediate feedback focused on improving academic performance.

Chapter 7 of the report, "Information Technologies: Opportunities for Advancing Educational Assessment," is especially useful for this discussion and will be of value to readers with interests in technology in education generally as well as in the context of K–12 math education.

Some digital enthusiasts hope that digital tools will ameliorate the social and educational inequities that our schools demonstrate and enforce. The Matthew Effect says otherwise, that is, the rich get richer [48]. As is well known, it is a concept first coined by sociologist of science Robert Merton. Taking a social capital approach to education, Haug warns us that, "if equity is ignored, the capacity-rich will get richer and the capacity-poor will get poorer. . . . Relying on local capacity to bring about the reform without attending to existing inequities makes it even more difficult for the least advantaged students to succeed in the standards-based environment" [10,

p. 27]. Schools and districts that succeed using traditional approaches to learning are also the ones most likely to succeed using digital and standards-based approaches, whether such achievement is based on common educational standards and high-stakes testing or not: “Without systematic attention to opportunity, the results of assessment simply recapitulate existing patterns of distribution of resources, both financial and social” [42, p. 92].

Digital libraries and information literacy initiatives can either help reinforce or undermine inequity, for example, by addressing the so-called digital divide. (See, e.g., Andy Carvin, Manuel Castells, the Digital Divide Network, and the series of reports of the National Telecommunications and Information Administration in the U.S. Department of Commerce [49–52].) Despite some assumptions to the contrary, the proliferation of digital tools makes teachers even more important, especially to address inequity in education. Teachers are as essential in digital environments as in print-based education, perhaps more so as students are required to develop new skills, to learn more actively, to do mathematical reasoning rather than just computation, and to develop quite sophisticated metacognition. Marlow Ediger [37, p. 9], echoing others, reminds us that a textbook is “not a self-teaching device but requires a knowledgeable, creative, and skillful teacher to implement its use.” Information literacy, especially as implemented in digital libraries as discussed in part 1, demands a similarly creative, skillful, motivated, and motivating teacher. In addition to their advanced functionalities supporting mathematical learning and pedagogy per se, digital libraries for K-12 math education can help teachers, students, and parents create new social networks to support learning and better leverage existing social networks.

It is, perhaps, this social network characteristic that is the greatest potential contribution of digital libraries to K-12 mathematics education, not advanced computational, retrieval, and display capabilities. As Jean Lave, Étienne Wenger, and many others make clear, knowledge is a result of social activity, and learning is inextricably bound to evolving and shared identities [44, 45, 53]. Thus, learning is a key link between community and self—digital libraries, particularly as designed and implemented in the context of information literacy, can be vital catalysts in this nexus of learning, identity, and community. In addition, as discussed throughout parts 1 and 2, the ability to communicate about math is an important component in developing and demonstrating expertise, especially in demonstrating the ability to identify and use appropriate terms and participate in important mathematical practices [42, p. 92].

Holding teachers accountable for the performance of their students in a standards-based environment also demands further investment in teachers. For example, teachers need considerably more professional development and greater encouragement to develop and nurture professional

social networks. They need particular help in designing and implementing new methods of assessment appropriate to an environment in which subject standards are the norm [10, p. 17].

This need is not obviated by the introduction of digital libraries into K–12 education. Quite the contrary—information literacy and the implementation of digital libraries in the classroom, as described in part 1 and above, require significant investment in the initial and ongoing training of teachers. This need for increased commitment to teachers' education to maximize the benefit of digital technologies in education is absolute. Otherwise, the substantial promise of DLs will not be achieved. For example, advanced digital environments provide multimedia opportunities important in many ways, for example:

- Students can produce many kinds of work, such as songs, art projects, games, graphics (whether still or motion), musical works, spatial representations, long-term projects, process and instrument control, and performances (e.g., [37]). All of these kinds of work are important to mathematical competency, whether in analog or digital environments. As Bruner famously said: “How can I know what I think until I represent what I do?” [40, p. 101]. These works, both static and performed, can be shared with others across space (locally and remotely) and time (they can be presented in real time, archived, and replayed).
- Because of their use of multiple modes to learn and to demonstrate learning, digital libraries can support students with differing abilities, including abilities that evolve over time: “There are typical learning pathways, but not a single path-way to competence” [42, p. 300]. A well-designed and well-integrated digital library supports multiple pathways to learning and multiple ways to demonstrate competence.
- Digital libraries can provide models and opportunities for students’ reasoning, development of language skills, counting and computational abilities, and similar methods of enhancing mathematical performance.
- Digital libraries also provide the means for demonstrating and recording competence in these areas.

The information literacy/digital library approach to K–12 mathematics education, especially the ability to generate, retrieve, use multimedia materials, and demonstrate competence in the use of mathematical concepts and terms, is clearly complementary to two major emphases in contemporary pedagogy: (1) the availability of multiple modes of learning and demonstration of learning, and (2) the necessity of multiple modes of assessment of students’ learning, that is, multiple methods of formative and summative assessment. As is commonly recognized, however, teachers need more than simple encouragement or threats to help their students achieve important educational goals using standards, information literacy, and digital tools.

Conversations about K–12 education, including mathematics education,

TABLE 2
RECOMMENDATIONS FOR THE DESIGN OF DIGITAL LIBRARIES IN PART 2

Characteristics of Successful Digital Libraries for K-12 Math Education
Support of learning goals and activities based on standards developed by local mathematics teachers and teachers' professional associations
Explicit links to and integration with these "content" standards
Reinforcement of existing "indigenous" mathematical literacies and bridging them to professional standards and practices
Standardization and flexibility/customization for local circumstances
Integration of educational policies and standards, curriculum implementation, and digital libraries
Emphasis on educational achievement through multiple methods of evaluation
Support of increased equity in education
Responsiveness to systematic review of copyright statutes, regulations, and case law

must recognize the complexity inherent in evaluating, improving, and integrating digital technologies into education. Most important, we must leverage the considerable social capital in teachers' classroom experience with an increased sensitivity to achieving equity in education. Such an overall approach to education is based on an understanding of the multiple stakeholders involved and on an articulation of some of the most important value conflicts among them [32, 33].

Recommendations

We propose the following recommendations based particularly on the discussion in part 2 of the adoption of educational standards, reactions to educational policy making, and ensuring pedagogic and political accountability. Table 2 summarizes these recommendations.

- The collections of digital libraries in K-12 math education should be managed based on learning goals and activities, especially educational standards developed by classroom teachers. These libraries must provide rich opportunities for students and instructors to access, evaluate, and use the collections, especially to create new objects and meanings. Digital libraries can help create the kind of environment envisioned by Rowan and Bourne [9, p. 14], "where students can work seriously in pairs of small groups to solve problems, share strategies, and then to discuss their ideas in the large group setting. Classrooms in which the focus is [simply] getting the answer and moving on do not foster this atmosphere and therefore do not encourage students to think like mathematicians."
- Digital libraries for math education must have explicit links to "content" standards developed by mathematics teachers, including those formu-

lated by local teachers and by professional associations. As discussed above, Artemis at the Center for Highly Interactive Computing in Education in figure 2 [15], Standard Connection [16], and ESCOT's Search and Rescue in figure 3 [17] are good examples of what digital libraries intended for schools can accomplish for communication, collaboration, and linking digital objects to so-called content standards. Using such approaches, the educational standards are more likely to become transparent and meaningful to educators, teachers, students, and parents. Through the use of the digital libraries, these stakeholders can understand what, how, and why students should learn, as well as what educational goals students should have achieved.

- Successful digital libraries will respond to and reflect local literacies and work practices while linking students and parents to professional standards and practices. As is increasingly recognized (e.g., [21, 53]), children and their parents possess many and sophisticated “indigenous” uses of mathematical material, for example, abilities to cook, shop, keep score in games of all kinds, determine salary rates, measure distances, gamble, compute taxes, calculate best price per unit, and the like. First, these mathematical abilities must be recognized and explicitly valued at school; then, good teachers, using all the tools at their disposal, including digital libraries, must help students and their parents bridge from these existing abilities to new ones demanded of them by standards developed by teachers’ professional associations and domain experts.
- Digital libraries for K–12 mathematics education must rely on local technical circumstances and infrastructures while being compatible with higher-level and external digital collections. This imperative animates all forms of local deployment and use of digital tools—how can any collection or system be sufficiently local but still use widely used standards for multiple platforms, machines, network capabilities, software packages, and the like? Customization complicates the processes of defining a digital library’s audience and encourages “overfragmentation of the information world” [1, p. 10]. In the same volume, Phil Agre notes that even schools can be “held hostage to global standards that emerge and develop a critical mass of users in other sectors” [54, p. 234]. Like every information service, DLs for K–12 mathematics education must be standardized to some extent while still being sufficiently flexible to reflect and build upon local needs, values, practices, and (material) conditions.
- Designers and implementers of digital libraries for K–12 mathematics education should consider how Civic Online [20] integrates educational policies, educational standards, curriculum implementation, and digital libraries, which are all essential components of improved mathematics education.

- Digital libraries must be among the tools that parents, teachers, and educational administrators use to emphasize educational achievement without relying exclusively on high-stakes, standardized testing. Such libraries can serve as important means for students to demonstrate achievement of important, subject-specific learning (tied explicitly to subject standards developed by classroom teachers) to themselves, to their parents and teachers, and to educational administrators and politicians. As Deborah Meier makes clear, the development of rigorous local standards supports local creativity and children's commitments to local institutions [2]. Such standards must be linked to achieving subject competencies and must not be considered as fundamentally distinct from them, as high-stakes testing makes almost a certainty. Overcoming what we might call "test-induced alienation" is an important component of equity [55].
- The achievement of increased equity in education, across linguistic, ethnic, geographic, and other divides, must be an explicit goal of significant digital initiatives, including those involving K-12 mathematics education [42, 48]. Enhanced communication functionalities for important stakeholder groups, especially students, parents, and teachers, and modification of designs to enhance the creation of local work-arounds and creative practices are important ways that digital libraries can contribute to the achievement of greater social equity [56].
- Digital library projects and implementations must involve continual scanning and review of intellectual property statutes, regulations, and case law. Digital initiatives in education that fail to involve careful observation of and adjustment to copyright and other national legislation, national regulation, and local rule making are not likely to achieve their goals. Relying on technologists or attorneys to recognize potential concerns and to develop appropriate policy responses will not be sufficient to ensure the achievement of educational and other social goals. Instead, it is imperative that classroom teachers as well as building-level and district-level leaders understand the overall constraints and opportunities that intellectual property policy instruments offer. Building and maintaining this kind of expertise is essential to achieving educational missions as well as to achieving other political goals. Professional associations and university-level faculty members and administrators will be essential components of developing intellectual property expertise at the school and district levels and keeping such expertise current.

These recommendations are offered with the understanding that local conditions and circumstances are the major constitutive factors in situated social research and in the (iterative) design, implementation, and evaluation of digital libraries [1].

Conclusion

The six-part framework for designing and understanding digital libraries for K–12 mathematics education described in these two papers includes (see fig. 1) information literacy, information organization, integrated learning, adoption of educational standards for K–12 mathematics learners and teachers, educational policy making, and accountability to multiple stakeholders and values for achieving the goals of K–12 math education. The framework can be evaluated by the extent to which it can help learners achieve competence in the three major modes of mathematical expression. Learners must be able to generate mathematical verbal descriptions of real-world situations employing the right mathematical concepts, draw (using appropriate tools and media) and read pictures that represent the important elements of these situations, and employ the appropriate figures, formulas, and mathematical operations to describe them. In particular, digital libraries offer remarkable collaborative and communicative tools that support these three modes of expression.

Sociotechnical analysis offers some value in thinking about digital libraries in K–12 mathematics education. Sociotechnical analysis, developed from the intersection of the human sciences and computing, attempts to discuss social and technical relations “even-handedly without putting one or the other in a black box whose contents we agree not to explore” (Bijker and Law [57], quoted in [34], p. 26). The current authors’ six-part framework has aimed to include consideration of the networks of people, technologies, documents, practices, and institutions [1] that form the context of digital libraries and K–12 mathematics education. Without such a holistic framework, digital libraries in education are not likely to succeed. They may underestimate learners’ competencies, ignore local and national politics, make too little of teachers’ existing expertise and social capital, overlook local work practices and social networks, or fail along any number of axes. We hope that this six-part framework will prove fruitful for other researchers, given the concerted program of naturalistic, computing, policy, algorithmic, and other forms of research that digital libraries demand.

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